Peace River Regional District
Water Quality Database and Analysis

Prepared for:

Peace River Regional District and Treaty 8 Tribal Association

Prepared by:

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Executive Summary

The Peace River Regional District (PRRD) in northeastern British Columbia (BC) encompasses 12 million hectares, representing nearly 13% of the total territory of BC. Until this project was completed, establishing the status of the water quality had remained a challenge due to the size of the region, the fact that it was sparsely monitored, but mostly due to the lack of coordination in data collection and sharing between the various agencies operating in the region.

GW Solutions Inc. has been retained by the PRRD to build a groundwater-surface water baseline for the watersheds in its region. The project was completed over a two-year period (2014 – 2016). This project was mainly funded by both the Real Estate Foundation of British Columbia (REFBC) and the PRRD. Other contributors included the Treaty 8 Tribal Association (T8TA), GW Solutions Inc. (in-kind contributions), and Interraplan Inc. (in-kind contributions).

GW Solutions has completed a compilation, sorting, formatting, and organization of publicly available data on surface water and groundwater quality in the PRRD. Data from 11,935 surface water samples from 364 locations, and 875 groundwater samples from 522 locations, going back to the 1943.

Access to data on water is difficult in the PRRD. What has been achieved through this project should improve public access to water related information.

GW Solutions has compared the results to applicable provincial and federal guidelines.

Quality control protocols based on electro-neutrality were used to reject non reliable samples.

GW Solutions has used Water Quality Indexes (WQI) to assign values indicative of their water quality to samples. The WQIs have been used to illustrate the water quality at stations over selected time periods. Maps have been produced illustrating whether the water quality is poor to excellent for the region and for each watershed.

The change in WQI has been used to estimate the improvement or decline of the water quality over time. Maps have been produced illustrating WQI trends for the region and for each watershed. They appear to indicate a general worsening of the water quality versus time.

GW Solutions has analyzed the data to classify the water samples per water type, based on the presence of the major ions constituting water. At the regional scale, the surface water appeared to originally be predominantly calcium-bicarbonate, and the groundwater predominantly calcium/sodium-bicarbonate/sulphate.

We observe an increasing presence of sodium and sulfate in surface water (after 2000), in groundwater (after 2000), and in spring water (after 2011).

We observe an increasing presence of chloride in surface water after 2000.

We observe an increase in mineralization of the groundwater from bedrock wells after 2011 (i.e., the major ions are present at a higher concentration).

However, we cannot draw the conclusion that there has been an increase over time because we don't have the dataset from the same surface water sampling locations (for surface water) or wells and springs (for groundwater).

Barium concentration has increased in groundwater at several locations over a relatively short time period. Such an increase is not expected under natural conditions. The observed increase in barium concentration in groundwater could possibly be a result of the intense drilling activity in the region, through mobilization of deep groundwater containing higher concentration of barium or the release of barium into the shallow aquifers during drilling via drilling fluids.

The lack of information on water, both on quality and quantity prior to the 1970s, has prevented the definition of the baseline before human activities started having a footprint both at the surface and in the subsurface.

The groundwater regime has been very poorly monitored and is still very poorly monitored. Aquifers need to be adequately characterized and monitored.

Data review has revealed the absence of adequate temporal and spatial monitoring of both surface water and groundwater prior to and concurrent with human activities that may impact water. A proper surface water and groundwater monitoring plan is urgently needed; it should be adequately planned and funded.

There is a profound absence of knowledge about the presence and migration of fluids in the intermediate zone of the subsurface, approximately located between a depth of 500 m and 2 km. This needs to be addressed in the areas of intense oil and gas activities. Adequate characterization and monitoring programs need to be designed and implemented very rapidly.

The following recommendations were passed at the August 25, 2016 PRRD Committee of the Whole meeting:

1. That the Board (of directors of the PRRD) acknowledges and affirms that it is the Province who is ultimately the steward and regulator for water in the Province of BC, and that the Province recognizes that the quantity and quality of our water supply is essential to public health and sustainable communities, and that, the PRRD has received the report regarding the studies done on watersheds in the Peace, which will be posted for public use.
2. That the newly developed database be presented to appropriate regulators and provincial decision makers and request that, in collaboration with the PRRD, a review of all updated information be completed biannually in order to continue with trend analysis.
3. That the Province be encouraged to share with the public, all new water information in a timely manner.

4. That the Province, through the North East Water Strategy Working Group (a working group that includes input of local knowledge on water initiatives), determines at risk watersheds or parts of watersheds and conducts further assessment to identify causes and create mitigation strategies.
5. That the BC Ministry of Environment and the Ministry of Forests, Lands and Natural Resource Operations be requested to create regulations to characterize and monitor the movement of fluids in the intermediate zone between the depths of 500 meters and 2,000 meters.
6. That the Province be requested to implement monitoring programs to continue to define water baselines both for quantity and quality in areas of the region that are poorly defined or monitored.

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A. Glossary

AQUIFER	An underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials (gravel, sand) from which groundwater can be extracted using a water well. (See also confined aquifers and unconfined aquifers.). Aquifers can be interconnected to other aquifers and surface water and can be present at various depths.
AQUITARD	An aquitard is a zone in the ground or bedrock that restricts the flow of groundwater from one aquifer to another, or from the surface to the subsurface. Aquitards are usually comprised of silt, clay, or non-porous rock of low hydraulic conductivity.
AQUICLUDE	A zone in the subsurface that prevents the movement of groundwater. An aquiclude is synonymous with a material being impervious to the flow of water. A thick layer of clay is an aquiclude.
BEDROCK	Solid rock underlying surficial deposits such as soil, alluvium or other unconsolidated material.
CONFINED AQUIFER	A confined aquifer is a fully saturated layer of permeable material that has a “confining” layer of low permeability material (aquitard or aquiclude) above it. The low permeability confining layer causes the aquifer to be under pressure so that when the aquifer is penetrated by a well, the water will rise above the top of the aquifer.
FLUVIAL DEPOSITS	Units of granular particles (silt, sand and gravel) deposited by a river.
FRACTURED BEDROCK AQUIFER	In solid rock (i.e. bedrock), groundwater is stored in the fractures, joints, bedding planes and cavities of the rock mass. Despite the potential for having voids (known as porosity), a rock can only act as an aquifer if those voids are saturated and connected via conduits such as fractures.
GEOGRAPHIC INFORMATION SYSTEM (GIS)	A geographical information system (GIS) is a software system designed to capture, store, manipulate, analyze, manage, and present spatial or geographical data.

GEOVOLUMES	Three-dimensional (3D) representations of geological or hydrogeological features. These are interpolated in 3D modelling software.
GLACIO-FLUVIAL DEPOSITS	Deposits of granular material left by glacial meltwater streams.
GLACIOLACUSTRINE	Deposits of mostly fine-grained material (silt, clay), deposited under water in lakes resulting from the melting of glaciers. Thick, glaciolacustrine deposits in the Peace River region were formed by repeated inundation by large, ice-dammed meltwater lakes.
GROUNDWATER	Groundwater is water found in the soil or rock below the surface where the pores and openings are filled with water.
HYDRAULIC CONDUCTIVITY	Hydraulic conductivity defines the capacity of a medium to transmit water.
HYDRAULIC GRADIENT	The hydraulic gradient is represented by the slope of the water table or the piezometer surface.
HYDROGEOLOGICAL GROUP	The hydrogeological group (HGG) represents the two dominant groundwater flow regimes and aquifer types: 1) flow through porous media in surficial aquifers, and 2) flow through fractured media in bedrock aquifers.
HYDROGEOLOGICAL UNIT	Hydrogeological units (HGU) represent one or more Material Classes that have similar hydrogeological characteristics and behaviors. These units are created by aggregating materials based on our understanding of hydrogeology and by assigning named aquifers directly to the borehole intervals.
HYDROGEOLOGY	The science of groundwater.
IMPERMEABLE	Impervious to flow of fluids.

INTERMEDIATE ZONE	Zone in the subsurface from approximately 500 m to 2 km. It contains fluids (water and gas). In the intermediate zone, the groundwater becomes more saline with depth as it is increasingly isolated from recharge by precipitation. Also, it has resided for a long period of time within the aquifer rock and will have dissolved various salts and minerals within the rock.
MARINE DEPOSITS	Sand, silt, and clay materials deposited under a marine environment.
MATERIAL CLASS	Material Classes are soil or bedrock types that are used to define as objectively as possible the information provided by drillers logs. They are used as an intermediate step to group or correlate geological information at the location of one well or a group of wells in the same area in order to estimate the geometry of aquifers, aquitards, and aquicludes.
OVERBURDEN	The layer of granular and unconsolidated material including soil, silt, sand and gravel overlying bedrock, which has been either transported from elsewhere or formed in place. Also referred to as surficial deposits.
PERMEABILITY	The property describing the capacity of a medium to transmit a fluid.
PIEZOMETRIC LEVEL	The elevation reached by water in a non-pumping water well completed in a confined aquifer. It also corresponds to the water table in unconfined aquifers.
PIEZOMETRIC SURFACE	A piezometric surface is the theoretical water elevation of all points in a pressurized, or confined aquifer. The surface can be interpolated from piezometric level point data using computer algorithms and the resultant surface can be contoured. Hydraulic gradients can be inferred from the resultant piezometric contours.
POROSITY	The volume of voids in a rock, sediment or soil. Porosity can be expressed as the ratio of the volume of voids in the medium to its total volume.
SALINITY	Salinity describes the concentration of salts in water. For groundwater in the intermediate zone, it can range from brackish up to 200,000 mg/l or more (for reference seawater is about 35,000 mg/l).

SATURATED ZONE	The subsurface zone in which all voids are filled by groundwater.
SEDIMENTARY ROCKS	Rocks formed from consolidation of loose sediments such as clay, silt, sand, and gravel.
SHALE	A fine-grained sedimentary rock, formed by the consolidation of clay, silt, or mud.
SHALLOW GROUNDWATER	Shallow groundwater is groundwater accessed from shallow surficial or bedrock aquifers, typically up to 300 m deep. Shallow groundwater has typically travelled for short periods of times (years, decades) in the subsurface and typically contains low concentrations of salts and other elements (e.g., metals).
STATIC WATER LEVEL (or STATIC LEVEL)	The level of water in a well that is not being influenced by groundwater withdrawals (e.g., pumping). The distance to water in a well is measured with respect to some datum, usually the top of the well casing or ground level.
SURFACE WATER	Surface water is water that can be seen on land. It includes lakes, rivers, streams, creek, ponds, wetlands. It is usually freshwater.
SURFICIAL DEPOSITS	Soil deposits overlying bedrock and consisting of clay, silt, sand, and gravel.
TILL	Till consists of a mixture of clay, silt, sand, gravel and boulders. Till is associated with glacial deposits.
TOTAL DISSOLVED SOLIDS (TDS)	Concentration of total dissolved solids (TDS) in groundwater expressed in milligrams per litre (mg/L), is found by evaporating a measured volume of filtered water sample to dryness and weighing this dry solid residue.
TRANSMISSIVITY	Rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

UNCONFINED AQUIFER	The saturated portion of a permeable soil or fractured bedrock medium where the water table is at a lower elevation that the top of the medium.
UNCONSOLIDATED DEPOSITS	Soil deposits that have not been subject to the pressure of the ice from glacial eras.
WATERSHED	A Watershed is the area of land that, due to its topography, collects water from precipitation and drains into a receiving surface water body (a river, a lake, a foreshore). Every piece of land is part of a watershed.
WATER CYCLE	The water cycle (also called the hydrologic cycle) is the cycle by which water circulates between the earth's oceans, atmosphere and land, involving precipitation as rain and snow, drainage in streams and rivers to the ocean, infiltration in the ground and flow in the subsurface as groundwater, and return to the atmosphere by evaporation and transpiration. Water is in continuous movement on earth, even at great depth in the subsurface. Sometimes, it moves fast (e.g., river), sometimes extremely slowly (e.g. in clay), but it always moves.
WATER TABLE	The surface corresponding to the top of the zone where all the voids in an aquifer are saturated with groundwater. It applies to unconfined aquifers. The depth to water in a non-pumping well completed in an unconfined aquifer will be the depth to the water table.
WELL SCREEN	Part of a water well where groundwater from the aquifer enters the well. It provides mechanical stability by preventing fine particles from entering the well. It should also offer enough opened area to allow groundwater to flow as freely as possible into the well.
WELL YIELD	The rate of groundwater that can be produced by a well.

B. Background

GW Solutions has been retained to build a water quality baseline for both surface water and groundwater. This project is funded by the Real Estate Foundation of British Columbia (REFBC), the Peace River Regional District (PRRD), Treaty 8 Tribal Association (T8TA), and in-kind contributions from GW Solutions Inc., and Interraplan Inc.

C. Questions and objectives

1 Key questions

The key questions to address were the following:

- How can water quality data be integrated and analyzed within a single frame?
- What is the status of both surface water and groundwater quality in the Peace River Region?
- Are there locations where we should be concerned about water quality?
- Is the water quality getting better? Worse?

2 Main objectives

The prime objective of the study was to build a database to define the baseline for the surface water and groundwater quality within the Peace River Regional District (PRRD). The second objective was to assess the quality of both surface water and groundwater within the PRRD by comparing water quality data to applicable water quality guidelines. The third objective was to estimate how the water quality is evolving with time. The fourth objective was to improve the knowledge about aquifers and about the groundwater regime in the PRRD.

D. Creation of a database

1 Surface water quality database

1.1 Methodology

The methodology used to develop the water quality database is summarized in Figure 1.

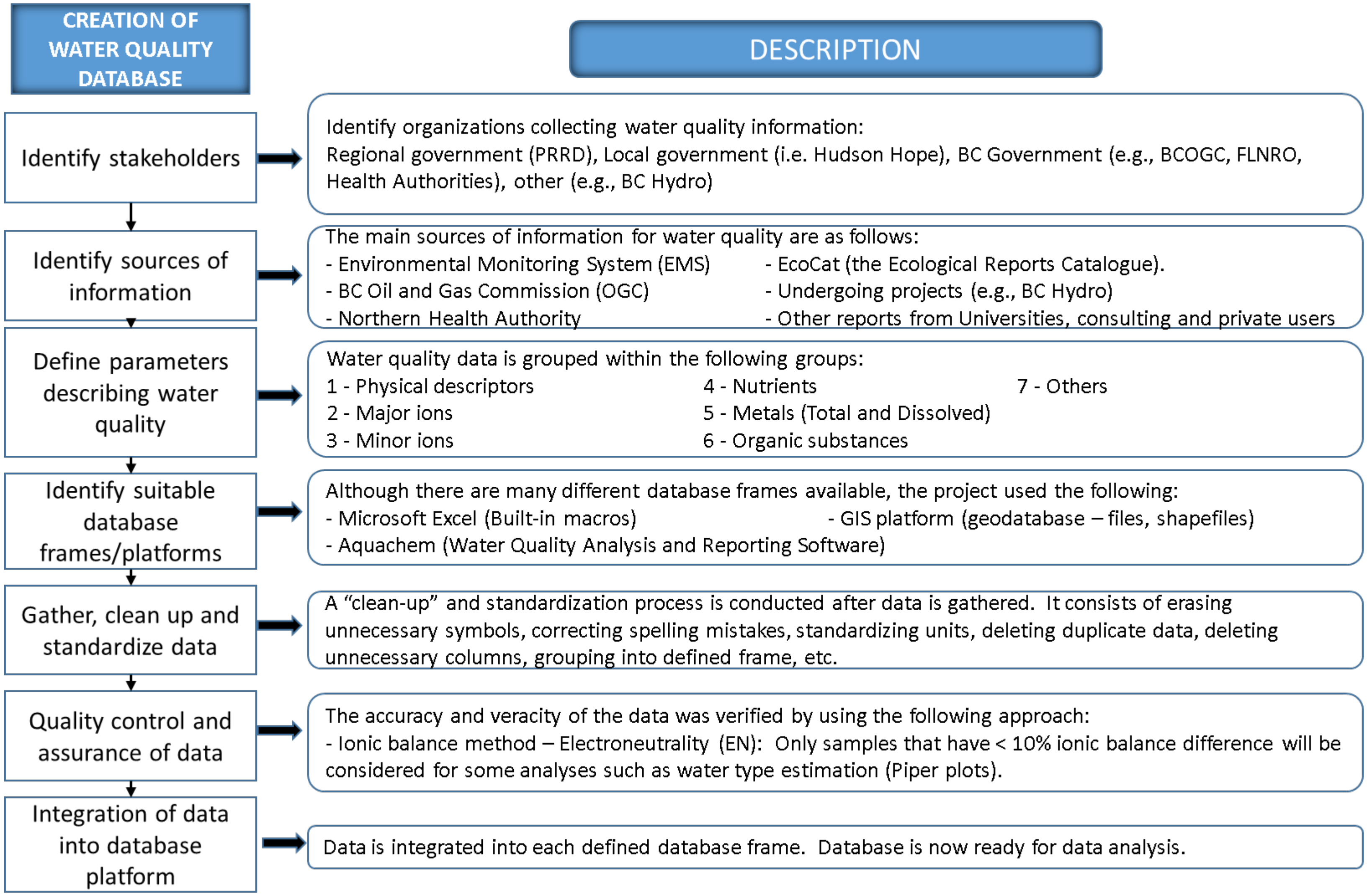


Figure 1. Schematic methodology used for creating the water quality database for the Peace River Regional District

1.1.1 Main sources of information.

1.1.1.1 Environmental Monitoring System (EMS)

The EMS is a water quality repository system created and maintained by the government of British Columbia. It includes chemical analysis results on air, water, and soil. The data can be filtered depending on the sampling locations. There are around 40 location types, but only five location types were considered for the non-treated surface water chemistry database, as summarized in Table 1. The data is in a csv file and it contains over 300 parameters.

There are approximately 6,900 non-treated surface water quality stations, containing over 0.5 million water quality results, within the entire province of BC. Within the PRRD, there are 326 stations with approximately 12,000 water chemistry results for non-treated surface water (data available up to February 2015).

Table 1. EMS location type data groups considered for the surface water quality database

Code	Location Type
13	LAKE OR POND
21	RIVER, STREAM OR CREEK
27	SPRING OR HOT SPRING
D2	SURFACE WATER NON-TREATED
D8	SURFACE WATER SOURCE

1.1.1.2 Northern Health Authority (NHA)

There are five health regions that cover the entire province of BC. The PRRD is within the Northern Health Region which covers 65% of the territory. The Northern Health houses water chemistry results for approximately 102 water supply systems (http://www.healthspace.ca/nha). Unfortunately, water quality data is not geo-referenced. In addition, data is only available in text file and parameters are not standardized. GW Solutions geo-referenced and standardized information from the NHA in order to incorporate it into the surface water quality database.

1.1.1.3 EcoCat, the Ecological Reports Catalogue

EcoCat provides public access to available reports and publications for the province of BC. GW Solutions did not explore further available surface water quality reports since most of the chemical results are stored within the EMS database.

1.1.1.4 BC Oil and Gas Commission (BC OGC)

The BC OGC has created a water portal (http://waterportal.geoweb.bcogc.ca) displaying water quality data for both surface water and groundwater. Most of the surface water quality results are obtained from the EMS and the Northern Health database; therefore, surface water quality data from BC OGC was not considered due to its redundancy.

Table 2. Number of monitoring stations for surface water quality included in the water portal BC OGC

Source of Information OGC surface water database	No of stations
BC MoE - Environmental Monitoring System (EMS)	334
Northern Health Authority (NHA)	75
Regulator - BC Oil and Gas Commission (BCOGC)	19
Total	428

1.1.2 Parameters.

Water quality parameters were framed into eight groups. The selection of parameters, included in the database, was based on the following criteria:

- The parameter is a key water chemistry indicator (baseline) and a water quality indicator for rivers or groundwater, and/or
- It has approved BC guidelines, and/or
- It is a potential contaminant of concern associated with human activity commonly found in the Peace River Region, and
- It meets the quality control protocol (described below).

Selected parameters are listed in the following table:

Table 3. Parameters considered within the surface water and groundwater quality database

No	Parameter group	Surface water Parameters	Groundwater Parameters
1	**PHYSICAL DESCRIPTORS**	Dissolved Oxygen	Dissolved Oxygen
		Hardness	Hardness
		pH	pH
		Specific Conductance	Specific Conductance
		Temperature	Temperature
		Total Dissolved Solids (TDS)	Total Dissolved Solids (TDS)
		Total Suspended Solids (TSS)	Total Suspended Solids (TSS)
		Turbidity	Turbidity
2	**MAJOR IONS**	Calcium (Ca)	Calcium (Ca)
		Magnesium (Mg)	Magnesium (Mg)
		Sodium (Na)	Sodium (Na)
		Potassium (K)	Potassium (K)
		Bicarbonate (HCO_3)	Bicarbonate (HCO_3)
		Carbonate (CO_3)	Carbonate (CO_3)
		Chloride (Cl)	Chloride (Cl)
		Sulfate (SO_4)	Sulfate (SO_4)
3	**MINOR IONS**	Fluoride (F)	Fluoride (F)
4	**NUTRIENTS**	Nitrate + Nitrite	Nitrate + Nitrite
		Nitrate (NO_3)	Nitrate (NO_3)
		Nitrite (NO_2)	Nitrite (NO_2)
		Ammonia (NH_3)	Ammonia (NH_3)

No	Parameter group	Surface water Parameters	Groundwater Parameters
		Total Phosphorus (P) (only for lakes)	Total Phosphorus
		Chlorophyll	-
5	**METALS**	Aluminum (Al)	Aluminum (Al)
		Antimony (Sb)	Antimony (Sb)
		Arsenic (As)	Arsenic (As)
		Barium (Ba)	Barium (Ba)
		Beryllium (Be)	Beryllium (Be)
		Boron (B)	Boron (B)
		Cadmium (Cd)	Cadmium (Cd)
		Chromium (Cr)	Chromium (Cr)
		Cobalt (Co)	Cobalt (Co)
		Copper (Cu)	Copper (Cu)
		Iron (Fe)	Iron (Fe)
		Lead (Pb)	Lead (Pb)
		Lithium (Li)	Lithium (Li)
		Manganese (Mn)	Manganese (Mn)
		Mercury (Hg)	Mercury (Hg)
		Molybdenum (Mo)	Molybdenum (Mo)
		Nickel (Ni)	Nickel (Ni)
		Selenium (Se)	Selenium (Se)
		Silver (Ag)	Silver (Ag)
		Strontium (Sr)	Strontium (Sr)
		Thallium (Tl)	Thallium (Tl)

No	Parameter group	Surface water Parameters	Groundwater Parameters
		Titanium (Ti)	Titanium (Ti)
		Uranium (U)	Uranium (U)
		Vanadium (V)	Vanadium (V)
		Zinc (Zn)	Zinc (Zn)
6	**OTHER ORGANIC SUBSTANCES**	Total Phenols Ex: chlorophenols	Total Phenols
		Pesticides : atrazine	
		Hydrocarbons - PAH Ex: Benzo(a)pyrene, Anthracene, benzene, toluene	PAH Ex: Benzo(a)pyrene, Anthracene.
		PCB	PCB
7	**OTHERS**	Total Organic Carbon (TOC)	-
8	**ISOTOPES**		Isotope 18O (H2O)
			Isotope 2H (H2O)
			Isotope 34S(SO4)
			Isotope 18O (SO4)
			Isotope 13C (DIC)
			Isotope d13C C1
			Isotope d13C C2

Physical descriptors often present strong daily and seasonal fluctuations. Temperature, dissolved oxygen and pH, which present daily fluctuations, make spatial and trend analysis easily biased. Due to this bias, these parameters were analyzed with care before drawing any conclusions.

1.1.3 Database platform.

The water quality database was built using three different platforms:

1.1.3.1 Microsoft Excel

Microsoft Excel is likely the most common tool to store and analyze numerical data; for ease of sharing data, we have used this program. Macros were built to facilitate the processing of the large data set. For instance, scatter plots, guideline exceedance analysis, and Marimekko charts were generated using automated processes.

1.1.3.2 Geographic Information System (GIS) platform

GIS platforms are designed to store, sort, analyze, manage, and present geographical data. QGIS and ArcGIS, for desktop, were the two main GIS programs used to integrate water quality data. Both software programs have similar capabilities; however, QGIS is an open source program with a free license.

1.1.3.3 Aquachem water quality analysis and reporting software

Aquachem is a commercially available water quality package based on Microsoft Access. It was used in data interpretation and visualisation. In addition, water quality guidelines, both federal and provincial, were included into the aquachem database.

1.2 Data quality control and assurance (QA/QC)

According to the BC Field sampling manual, both laboratory and sampling QA/QC should be part of water quality sampling. The Canadian Association for Laboratory Accreditation Inc. (CALA) is responsible for assuring the quality of Laboratory services. In addition, all the samples from the EMS database are from CALA accredited laboratories and have met BC MoE QA/QC requirements (e.g., sampling QA/QC includes blanks, duplicates, etc.). Nevertheless, GW Solutions applied a quality control method, based on electro-neutrality, to control the quality of the entire dataset.

1.2.1 Electro-neutrality

The most common method used to verify the quality of the lab results is through calculation of the ionic balance for each sample. The ionic balance is based on the fact that water should be electrically neutral. The units used in the equation are in milli-equivalents (meq):

$$\sum Cations = \sum Anions$$

The lack of equilibrium between anions and cations, also known as electro-neutrality, is calculated as follows:

$$\mathrm{E.N.}\,(\%\ difference) = \left|\frac{\sum cations - \sum anions}{\sum cations + \sum anions}\times 100\right|$$

Chemical results with E.N. up 10% are considered acceptable.

Results for ionic balance (E.N.) can be presented as a frequency histogram as shown in Figure 2 (a) and (b). The first figure (a) represents an electro-neutrality histogram taking into account all the samples that have at least one ion analyzed (4,672 samples). Almost 50% of the samples (2,260) have an E.N. of less than 10%. The E.N. greater than 60% represents the samples that have very few ions analyzed, most of them being minor ions.

Figure 2 (b) presents a more realistic histogram, considering only samples that have at least three major cations and three major anions analyzed totaling only 629 samples. Taking into account this consideration, 86% of the samples are within 10% of the calculated E.N. However, if we consider only one cation and one anion (2,260 samples) then 75% of the samples have E.N. less than 10%.

E.N. greater than 10%, may be due to:

- Lab error;
- Not all the major cations and/or anions were analyzed or reported; and
- A major dissolved constituent has not been taken into account in the calculation of the ionic balance.

Only samples that have an electrical imbalance less than 10% are used for defining the general type of water (major ions). This population includes 2,260 samples. The samples that have an electrical imbalance greater than 10% are kept in the database for exceedances analysis and concentration mapping.

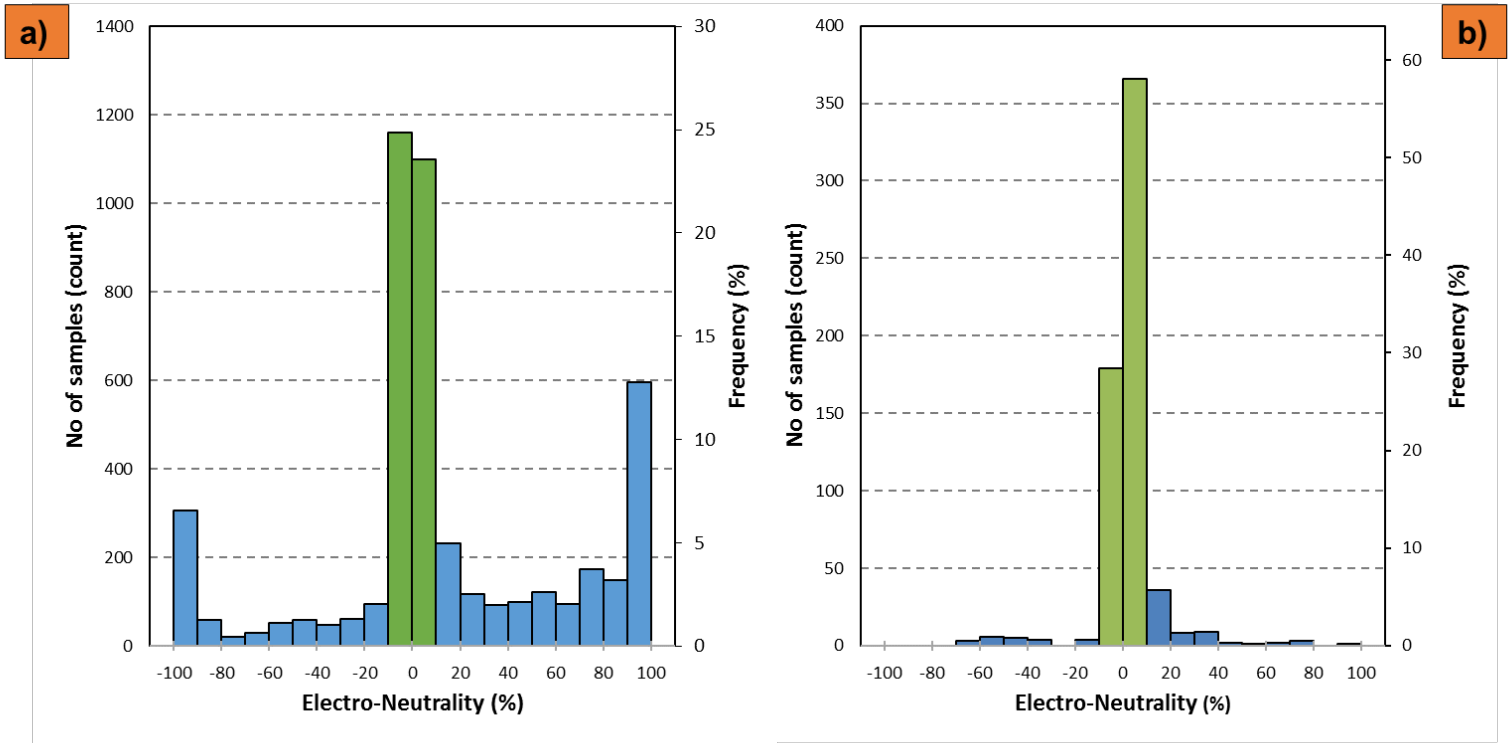


Figure 2. Frequency histogram of Electro-Neutrality: a) considering samples that have at least one ion analyzed, b) considering samples that have at least three major cations and three major anion analyzed

1.3 Stations and samples

The PRRD comprises 27 watersheds. Each watershed covers between 2% and 6% of the total area of the PRRD (119,200 km^2). There are close to 12,000 (11,935) surface water samples for the PRRD. Figure 3 shows watershed classification based on the number of water quality stations organized by source of information. The number of stations and samples vary widely. Poorly populated watersheds, where very little human activities are conducted, are sparse in data. Five watersheds (Lower Peace River, Murray River, Upper Piece River, Lower Beatton River, and Pine River) show the highest number of stations and samples, representing over 90% of the water samples of the database.

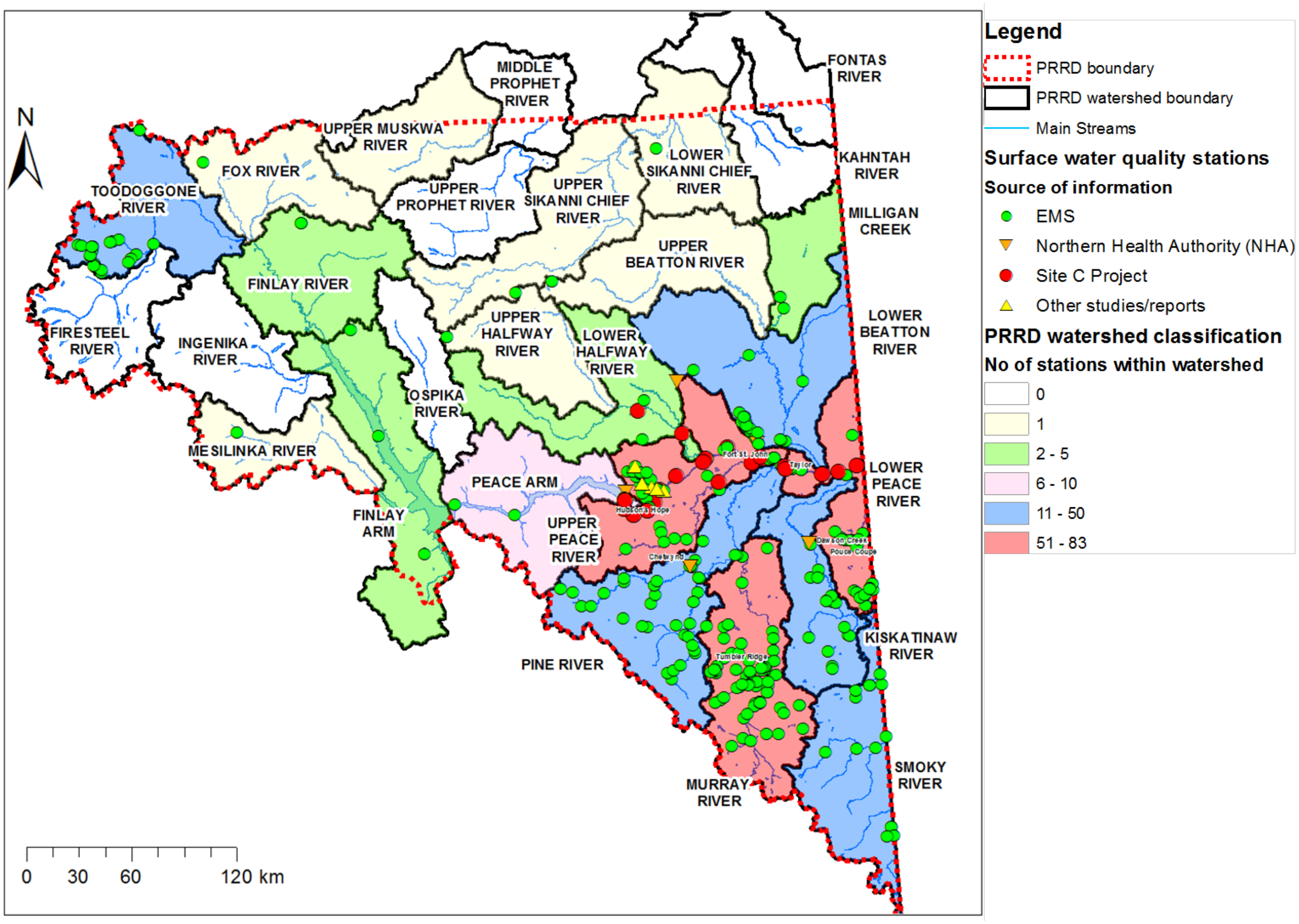


Figure 3. Watershed map showing number of surface water quality stations and source of information

1.4 Water quality guidelines

There are two sets of guidelines that can be applied in British Columbia. The first set was developed by the federal government and the second was developed by the Province of British Columbia. Both sets of guidelines are presented in Table 4.

Table 4. Set of guidelines considered within the data base for exceedance analysis

	Federal Guidelines	Provincial Guidelines	
CCME	Aquatic Life Freshwater Short Term	Aquatic Life Freshwater Chronic (30-Day Mean)	BC MoE
CCME	Aquatic Life Freshwater Long Term	Aquatic Life Freshwater Acute (Maximum)	BC MoE
CCME	Agriculture Livestock	Agriculture Livestock Watering Chronic (30-Day Mean)	BC MoE
		Agriculture Livestock Watering Acute (Maximum)	BC MoE
CCME	Agriculture Irrigation	Agriculture Irrigation Chronic (30-Day Mean)	BC MoE
		Agriculture Irrigation Acute (Maximum)	BC MoE
FPTWGRWQ	Recreational	Recreational Chronic (30-Day Mean)	BC MoE
		Recreational Acute (Maximum)	BC MoE
		Wildlife Chronic (30-Day Mean)	BC MoE
		Wildlife (Acute Maximun)	BC MoE
FPTCDW	Guidelines for Canadian Drinking Water Quality (GCDWQ)	Drinking Water Chronic (30-Day Mean)	BC MoE
		Drinking Water Acute (Maximun)	BC MoE

Both sets of guidelines have been incorporated into the database GW Solutions has created for this project. Any guideline, or set of guidelines, either federal or provincial, can be selected when generating tables, graphs or maps.

1.4.1 Federal guidelines

The first set consists of four different guidelines (aquatic life - both chronic and acute, agriculture - both livestock and irrigation, recreational, and drinking water quality) as summarized in Table 4. These guidelines were developed by the Canadian Council of Ministers of the Environment (CCME) except for the last two guidelines. The Canadian Drinking Water Quality (GCDWQ) was developed by the Federal-Provincial-Territorial Committee on Drinking Water of the Federal-Provincial-Territorial Committee on Health and the Environment (FPTCDW), and Recreational guidelines were developed by Federal-Provincial-Territorial Working Group on Recreational Water Quality (FPTWGRWQ) of the Federal-Provincial-Territorial Committee on Health and the Environment.

The established limits for 186 parameters considered within the four sets of guidelines are presented in Appendix 1. The Aquatic Life Fresh Water Long Term guideline is the most stringent and includes the largest number of regulated parameters (130 out of 186 parameters). The Drinking water guidelines lists 94 regulated parameters. The Agriculture guideline for both irrigation and livestock lists 80 and 88 regulated parameters, respectively. Finally, the guideline for recreational use lists only three regulated parameters.

1.4.2 Provincial guidelines

The Ministry of Environment of British Columbia (BC MoE) has developed a set of more specific guidelines, as listed in Table 4. The Aquatic Life guideline is the most stringent, for most of the parameters. The BC MoE guidelines list up to 44 parameters (as of February 2016). In addition, interim thresholds are presently used for 14 parameters within the BC MoE guidelines. Appendix 1 summarizes the 55 parameters with established acceptable limits considering the five sets of guidelines.

Acceptable limits for some parameters are not constant values, but depend on other parameter values such as Methyl Mercury content, temperature, pH or hardness (Aquatic Life guideline) or crop, soil drainage, soil pH, pH or temperature (Agriculture for Irrigation guideline). These parameter dependant guidelines are also included in Appendix 1.

2 Groundwater quality data base

2.1 Methodology

The methodology adopted to build the groundwater quality database is basically similar to the methodology used for surface water, as presented in Figure 1.

2.1.1 Main sources of information.

The sources of information for the groundwater quality in the PRRD are grouped into four categories summarized in Table 5 and explained in detail below.

Table 5. Main sources of information for the groundwater quality database including number of stations and samples across the PRRD

Source of information	Public accessibility	Number of stations	No of samples
Northern Health Authority (NHA)	Yes - not geo-referenced	85	282
NEBC FLNRO - SFU	Not publicly available	178	198
BC MoE Well Report Water Chemistry - OGC	Yes - no account required	162	193
Environmental Monitoring system (EMS)	Yes - requires a BCID account	90	149
Other studies/reports	Yes - depending on the project	16	53
Total		522*	875

** there are 522 stations across the PRRD where 6 stations have more than one source of information*

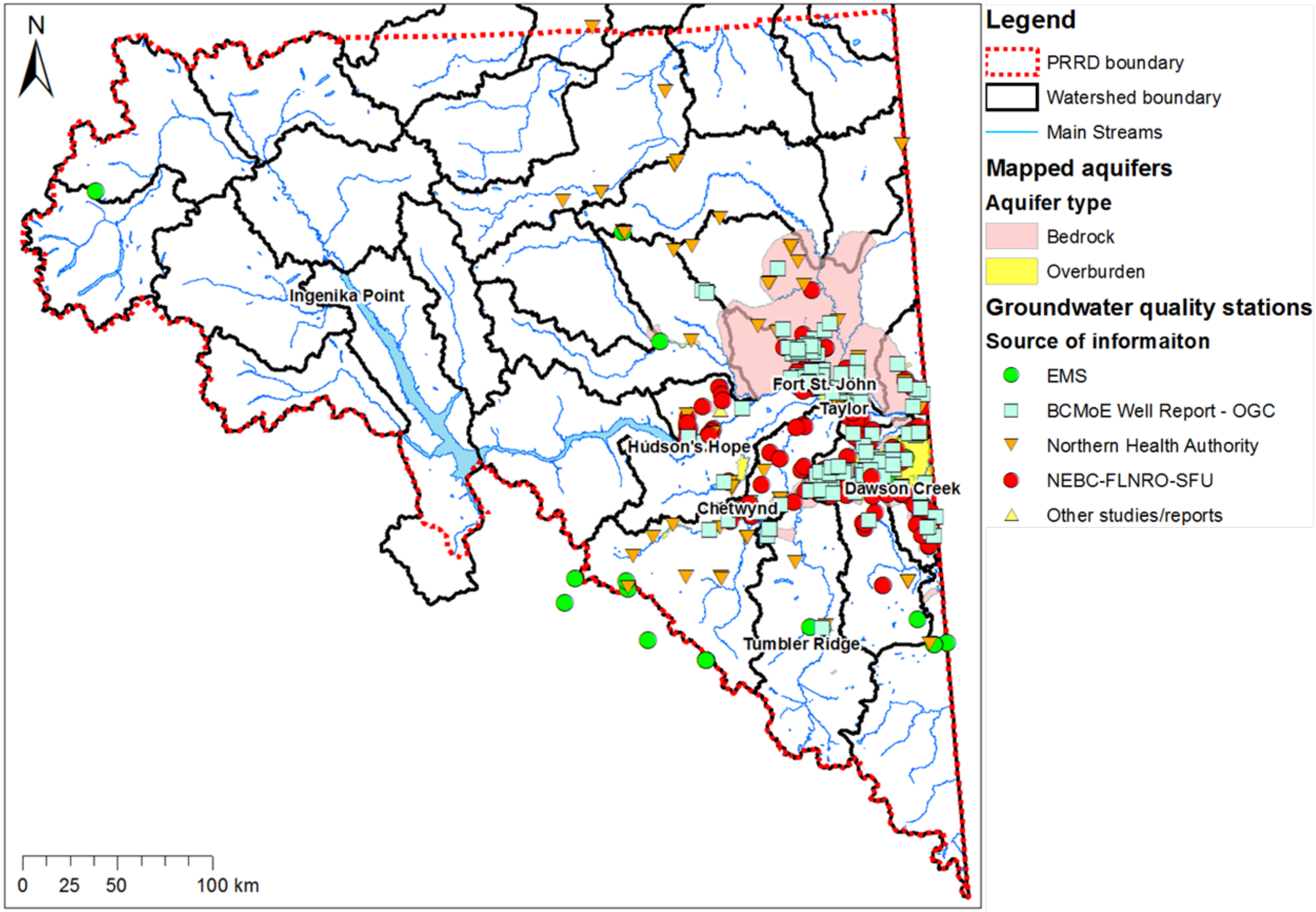


Figure 4. Groundwater stations across the PRRD classified by source of information.

2.1.1.1 Northern Health Authority (NHA)

When downloading water quality information from the NHA website (http://www.healthspace.ca/nha), data is not separated by source type (surface/groundwater) nor by treated/non-treated water samples. Therefore, the first step was to group water quality samples by sampling source and considering only non-treated water.

Over 280 groundwater quality samples from 85 sampling stations were included in the groundwater quality database. In addition, the NHA data has the largest number of sets of data, as well as the oldest samples found within the PRRD.

2.1.1.2 NEBC-FLNRO-SFU

As part of the North East BC project (NEBC), Ministry of Forest Lands and Natural Resource Operations (FLNRO) and Simon Fraser University (SFU) have started characterizing the groundwater quality in Northeast BC. We had access to data from approximately 200 samples from 178 stations. This information is still not publicly available; however, it was temporarily included in the database and used in our analysis.

2.1.1.3 Environmental Monitoring system (EMS)

Data from the EMS was downloaded and filtered to include non-treated groundwater that corresponds to six location types, as summarized in Table 6.

The EMS database lists over 3,100 stations and approximately 50,000 groundwater quality samples, for the whole province. Across the PRRD there are 90 groundwater quality stations and 149 samples.

Table 6. EMS location type data groups considered for the groundwater quality database

Code	Location Type
27	SPRING OR HOT SPRING
33	WELL
38	MONITORING WELL
45	OBSERVATION WELL (GROUNDWATER)
D4	GROUNDWATER NON-TREATED
D7	GROUNDWATER SOURCE

2.1.1.4 BC Oil and Gas Commission (BC OGC)

The BC OGC, through the water portal, includes groundwater quality data for 251 sampling locations with known numbers of samples. The BC MoE Well Report Water Chemistry has the largest set of samples and generally each monitoring location has one sampling event. GW Solutions downloaded, standardized and included the data that corresponds to BC MoE Well Report Water Chemistry (162 stations and 193 water quality samples) into the PRRD database.

2.1.1.5 EcoCat, the Ecological Reports Catalogue and other studies

There is a large number of reports/studies in the EcoCat website (http://a100.gov.bc.ca/pub/acat/public/welcome.do). Data could be downloaded using different filters such as geography (watershed, region), and specific business area (water information). GW Solutions was able to gather some water quality samples which were included into the group of sources of information labelled as "other studies/reports". In addition, GW Solutions has been involved in different projects within the PRRD. Data from these projects were included in the database.

2.1.2 Water quality frame and template.

The template, used for describing the groundwater component, is similar to the surface water quality template. The only difference being that this template includes isotopes.

2.2 Quality assurance and control analysis

2.2.1 Electro-neutrality

Electro-neutrality was calculated using the same approach as used for the surface water. Samples with electro-neutrality between -10% and +10% were included in the water type analysis. Missing bicarbonate and carbonate data were modelled from total Alkalinity and pH using the USGS PHREEQC program (Parkhurst and Appelo, 1999) included into the Aquachem software.

Figure 5 shows the histogram for the electro-neutrality analysis. Figure 5 a) represents the histogram for all the samples with at least one major ion tested (821 samples out of 875 samples). 53% of the samples (437) are within 10% range of electro neutrality. The imbalanced samples (90% - 100%- 328 samples) were typically due to sole analyses of cations, or anions. The remaining imbalanced samples represents only 6% of the total samples. Figure 5 b) shows the electro neutrality histogram considering samples that have at least three major cations and three major anions (458 total samples) tested. 93% (424) of the samples have E.N. less than 10%.

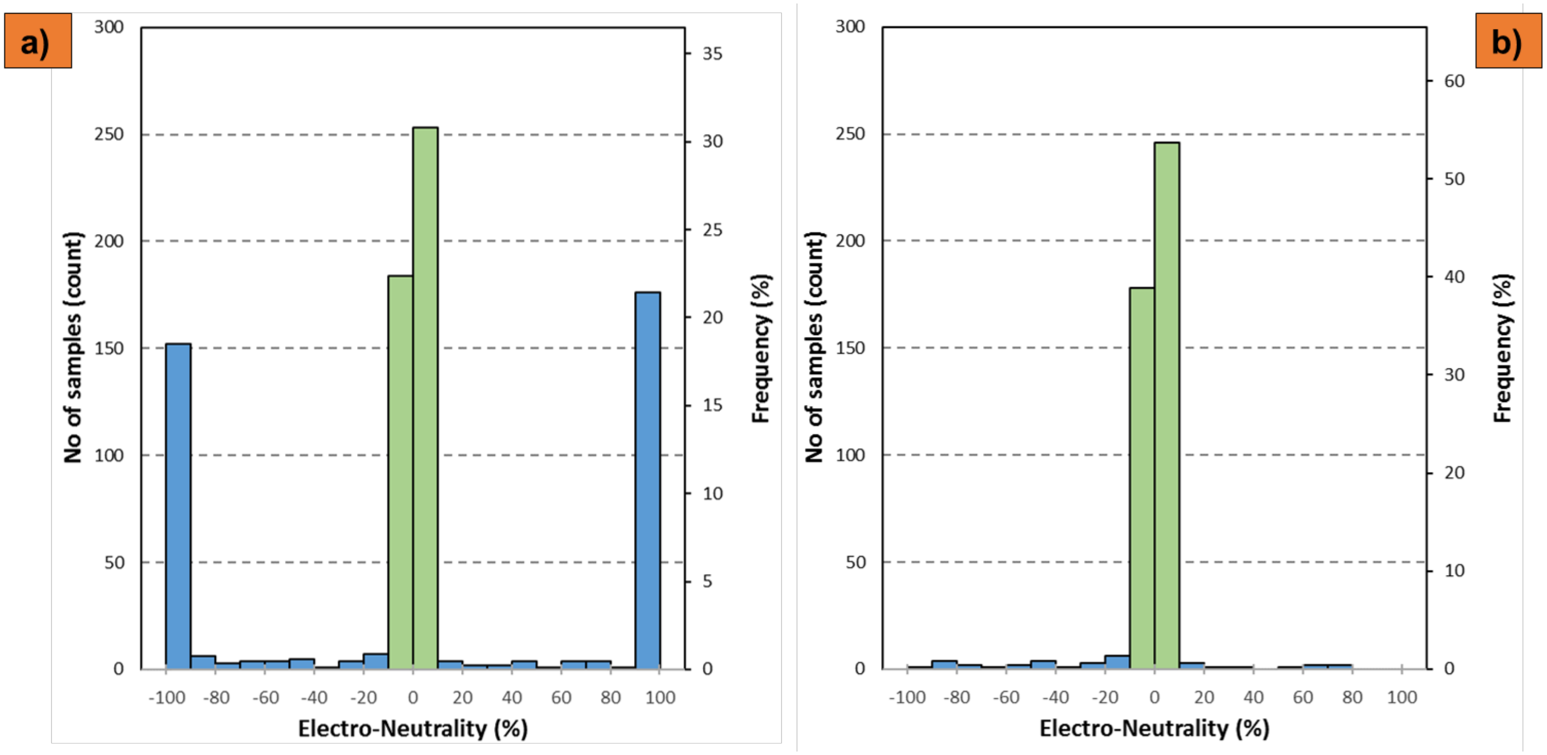


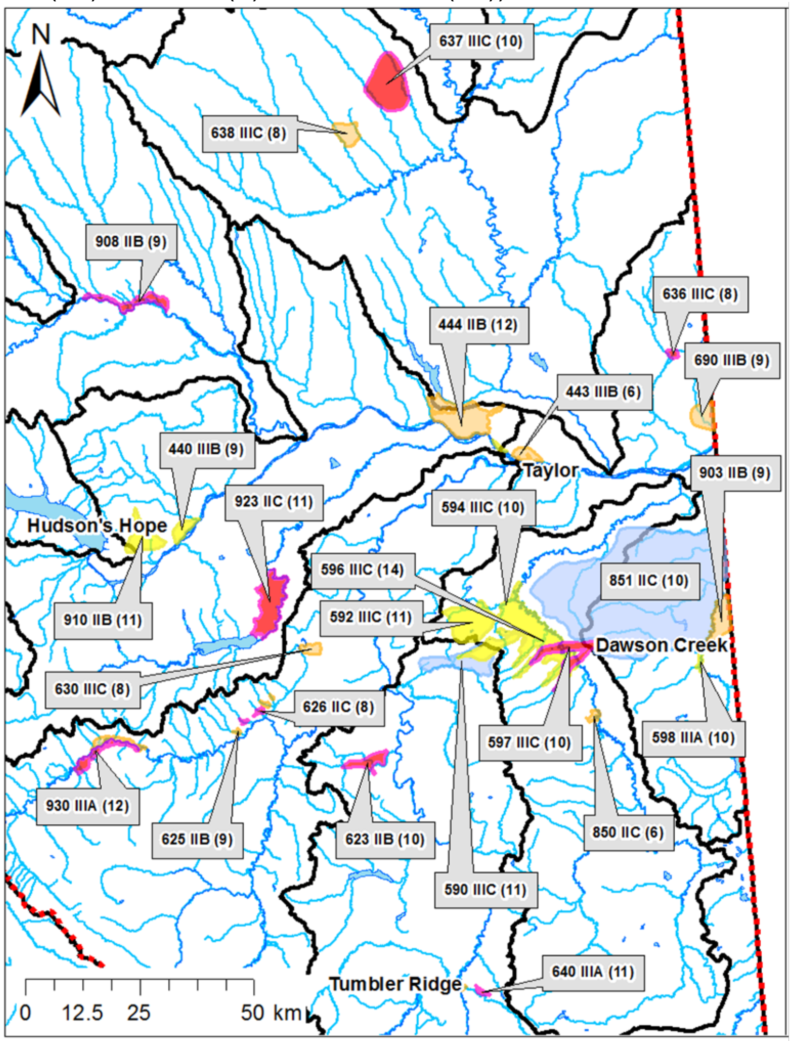
Figure 5. Frequency histogram of Electro-Neutrality for groundwater samples: a) considering samples that have at least one ion analyzed, b) considering samples that have at least three major cations and three major anions analyzed.

2.3 Stations and samples

There are 55 mapped aquifers within the PRRD (23 are bedrock aquifers and 32 are surficial (overburden) aquifers). There are 522 stations with 875 samples across the PRRD. As part of the groundwater PRRD project study presented in the physical hydrogeology component, each well with WTN has been assigned an aquifer type (surficial or bedrock) and aquifer name (mapped aquifer). Approximately 51% of the stations were reported with a well tag number (WTN) or well ID number. For instance, all the stations obtained from the Ministry of Environment Well Report Water Chemistry / OGC have a WTN reported in the water quality result. Stations located outside of the boundary of a mapped aquifer were assigned an “undefined-bedrock/undefined-surficial” qualifier. They represent 37% of the water quality stations. The aquifer type/name assignation for the remaining 12% of the stations were inferred based on location, nearby completed groundwater wells, and surficial/bedrock geology.

Figure 6 shows the bedrock aquifers classified by the number of stations, the number of samples and the time periods for which data is available. Four bedrock aquifers have the highest number of stations and number of samples. One aquifer is located near Fort St. John north of the Peace River (451 IIIC (12)), the remaining three are located south of the Peace River around Dawson Creek (591

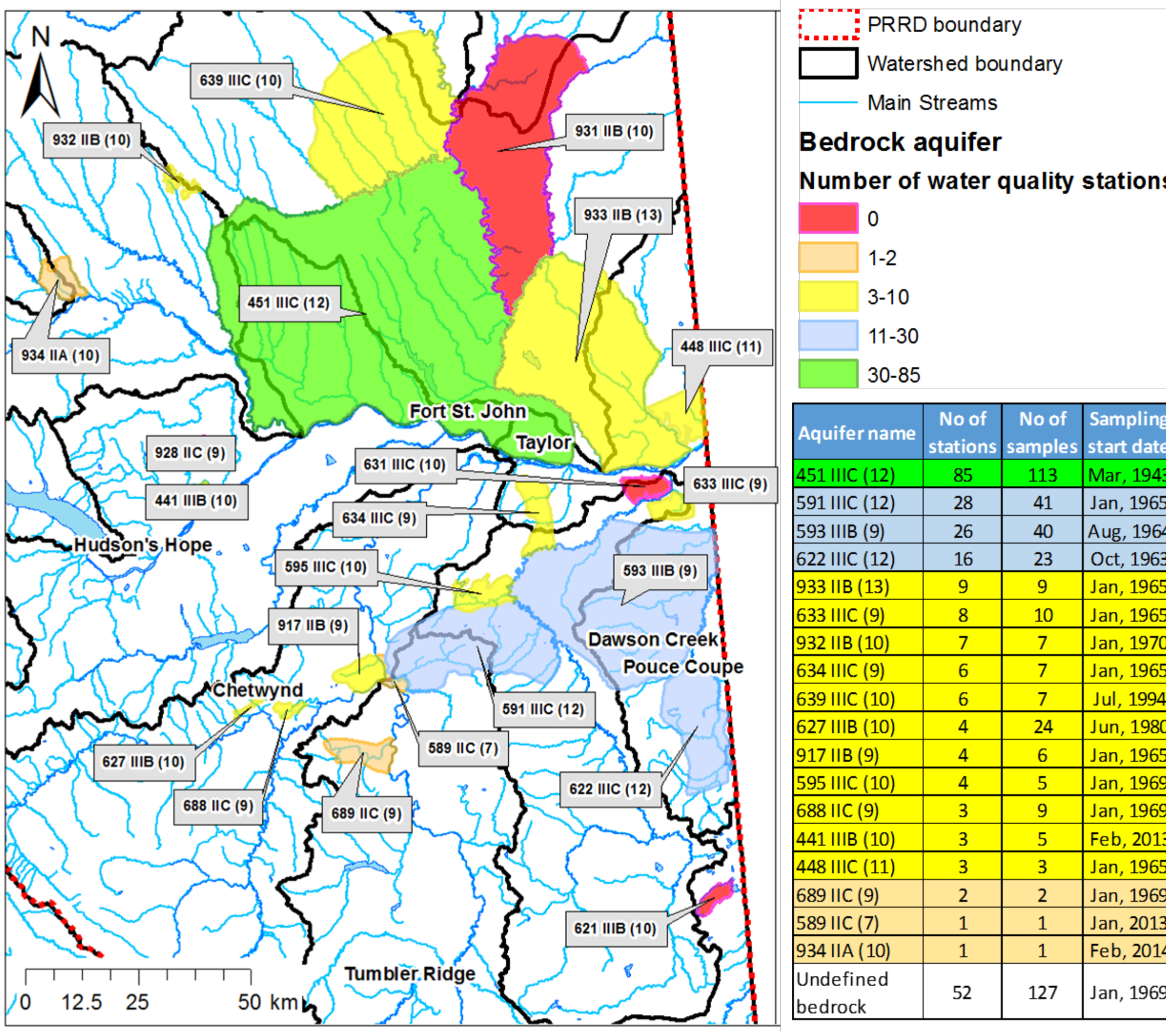
IIIC (12), 593 IIIB (9), and 622 IIIC (12)).



Aquifer name	No of stations	No of samples	Sampling start date	Sampling end date
851 IIC (10)	23	26	Jan, 1965	Feb, 2013
590 IIIC (11)	11	12	Sep, 1963	Mar, 2015
910 IIB (11)	9	17	Aug, 1985	Sep, 2014
594 IIIC (10)	9	12	Jan, 1965	Feb, 2013
442 IA (12)	6	32	Apr, 1994	Nov, 2010
440 IIIB (9)	5	12	Oct, 2001	Sep, 2014
592 IIIC (11)	5	5	Jan, 1965	Jan, 2013
598 IIIA (10)	3	5	Mar, 1963	Feb, 1975
596 IIIC (14)	3	4	Jun, 1967	Jul, 1969
628 IIB (8)	2	2	Jan, 1969	Jan, 1969
929 IIB (9)	1	30	Jul, 1995	May, 2011
443 IIIB (6)	1	12	Oct, 1998	Jun, 2002
635 IIA (15)	1	10	Jul, 1985	Oct, 2013
850 IIC (6)	1	2	Jan, 2012	Mar, 2014
444 IIB (12)	1	1	Jun, 1977	Jun, 1977
625 IIB (9)	1	1	Jan, 1969	Jan, 1969
629 IIB (8)	1	1	Nov, 2012	Nov, 2012
630 IIIC (8)	1	1	Nov, 2011	Nov, 2011
638 IIIC (8)	1	1	Jan, 1965	Jan, 1965
690 IIIB (9)	1	1	Jan, 1965	Jan, 1965
903 IIB (9)	1	1	Jan, 1965	Jan, 1965
Undefined overburden	146	202	Feb, 1964	Nov, 2014

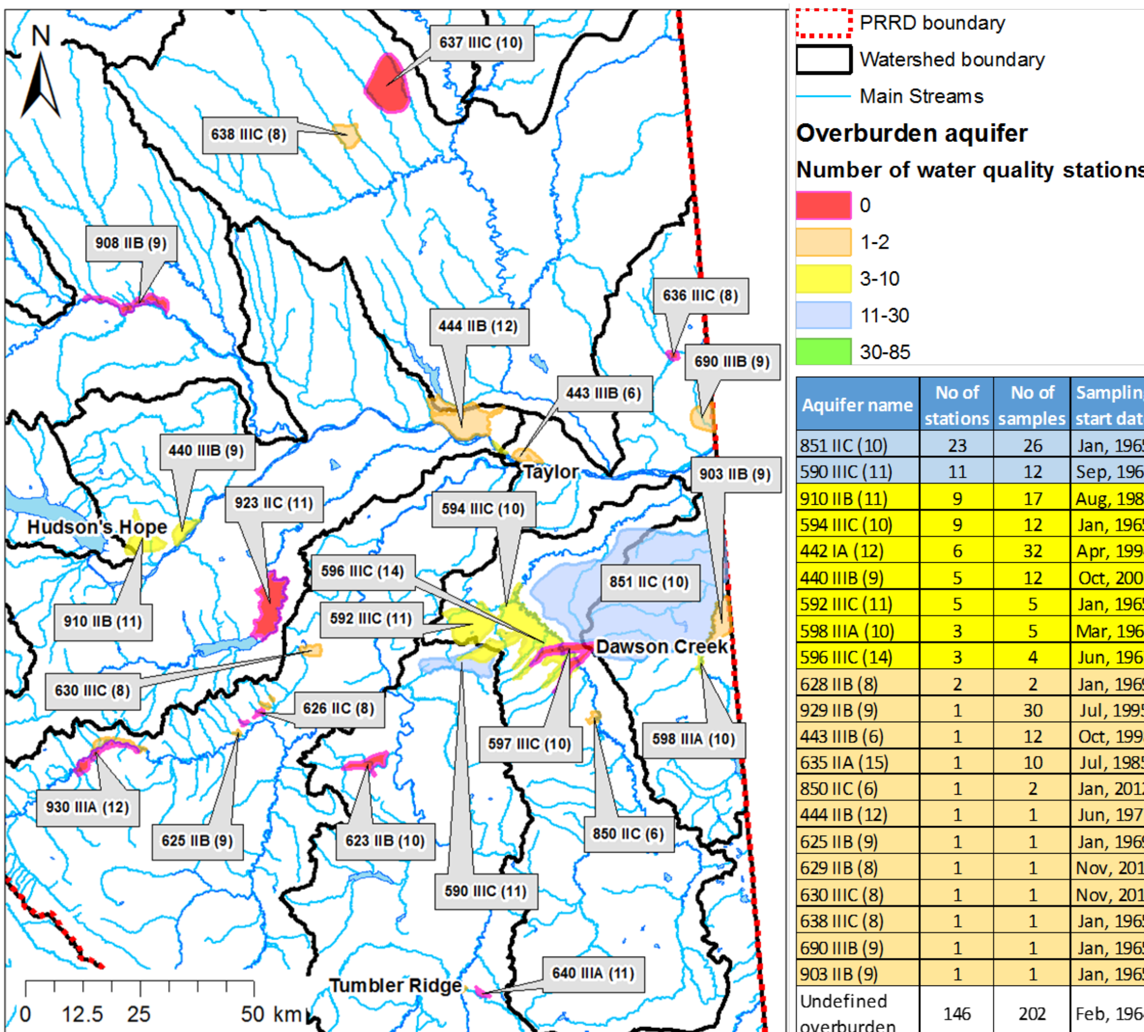
Figure 7 shows similar information for overburden aquifers. These aquifers are much smaller and usually located near surface water bodies. Aquifers 851 IIC (10) and 590 IIIC (11) have the highest number of samples and stations. In addition, aquifers 442 IA (12) and 929 IIB (9) have over 30 samples each, although they only have six and one stations, respectively.

Approximately 20 stations correspond to springs, 146 stations to undefined/unmapped surficial aquifers, and 52 stations to undefined/unmapped bedrock aquifers.



Aquifer name	No of stations	No of samples	Sampling start date	Sampling end date
451 IIIC (12)	85	113	Mar, 1943	Oct, 2014
591 IIIC (12)	28	41	Jan, 1965	Mar, 2015
593 IIIB (9)	26	40	Aug, 1964	Jul, 2014
622 IIIC (12)	16	23	Oct, 1963	Oct, 2014
933 IIB (13)	9	9	Jan, 1965	Oct, 2014
633 IIIC (9)	8	10	Jan, 1965	Mar, 2014
932 IIB (10)	7	7	Jan, 1970	Oct, 2012
634 IIIC (9)	6	7	Jan, 1965	Oct, 2014
639 IIIC (10)	6	7	Jul, 1994	May, 2014
627 IIIB (10)	4	24	Jun, 1980	Aug, 2014
917 IIB (9)	4	6	Jan, 1965	Jun, 2006
595 IIIC (10)	4	5	Jan, 1969	Dec, 2011
688 IIC (9)	3	9	Jan, 1969	Nov, 2014
441 IIIB (10)	3	5	Feb, 2013	Nov, 2014
448 IIIC (11)	3	3	Jan, 1965	Aug, 2014
689 IIC (9)	2	2	Jan, 1969	Sep, 1981
589 IIC (7)	1	1	Jan, 2013	Jan, 2013
934 IIA (10)	1	1	Feb, 2014	Feb, 2014
Undefined bedrock	52	127	Jan, 1969	Nov, 2014

Figure 6. Bedrock aquifer classification based on number of stations, number of samples and time periods covered.



Aquifer name	No of stations	No of samples	Sampling start date	Sampling end date
851 IIC (10)	23	26	Jan, 1965	Feb, 2013
590 IIIC (11)	11	12	Sep, 1963	Mar, 2015
910 IIB (11)	9	17	Aug, 1985	Sep, 2014
594 IIIC (10)	9	12	Jan, 1965	Feb, 2013
442 IA (12)	6	32	Apr, 1994	Nov, 2010
440 IIIB (9)	5	12	Oct, 2001	Sep, 2014
592 IIIC (11)	5	5	Jan, 1965	Jan, 2013
598 IIIA (10)	3	5	Mar, 1963	Feb, 1975
596 IIIC (14)	3	4	Jun, 1967	Jul, 1969
628 IIB (8)	2	2	Jan, 1969	Jan, 1969
929 IIB (9)	1	30	Jul, 1995	May, 2011
443 IIIB (6)	1	12	Oct, 1998	Jun, 2002
635 IIA (15)	1	10	Jul, 1985	Oct, 2013
850 IIC (6)	1	2	Jan, 2012	Mar, 2014
444 IIB (12)	1	1	Jun, 1977	Jun, 1977
625 IIB (9)	1	1	Jan, 1969	Jan, 1969
629 IIB (8)	1	1	Nov, 2012	Nov, 2012
630 IIIC (8)	1	1	Nov, 2011	Nov, 2011
638 IIIC (8)	1	1	Jan, 1965	Jan, 1965
690 IIIB (9)	1	1	Jan, 1965	Jan, 1965
903 IIB (9)	1	1	Jan, 1965	Jan, 1965
Undefined overburden	146	202	Feb, 1964	Nov, 2014

Figure 7. Overburden aquifer classification based on number of stations, number of samples and time periods covered.

E. Water quality analysis

1 Surface water quality analysis

1.1 Water type determination

1.1.1 Methodology

The water type, or hydrochemical facies, is determined by the main anion and cation constituting the water. Piper diagrams are commonly used to represent and visualize the key ions present in water, to compare water samples, and to illustrate changes in water quality. The major chemical constituents in groundwater and surface water are usually Calcium (Ca), Potassium (K), Sodium (Na), and Magnesium (Mg) for the cations, and Sulfate (SO4), Chloride (Cl), Bicarbonate (HCO3) and Carbonate (CO3) for the anions.

Water type was determined by using two programs: Aquachem and a USGS macro for excel. When using Aquachem, all the ions were included; however, only the major ions (Ca, Na, K, Mg, SO4, HCO3, CO3 and Cl) were included when using the USGS excel macro. Excel Piper plots were completed for each watershed classified by station ID. In addition, a second set of Piper plots was created to assist in identifying whether the flux in the streams resulted in a change in water chemistry. The data was split into two sub-sets:

- Samples taken during the months of May, June and July. These months typically correspond to periods of higher flows, according to the hydrographs of the rivers in the region.

- The samples taken in the remaining months representing the low-flow period.

A map of the different water types (obtained through Aquachem) identified in the Peace River Region was created (Figure 12 and Figure 13). In addition, a series of maps, for all the watersheds with water type data, was generated showing the evolution of water type distributed spatially (Appendix 2).

A series of Mekko charts (Marimekko) were generated to visualize and assess the change in water type both within the watershed and along the Peace River (headwaters to the mouth). Only major ions were selected for this analysis. The percentage of the major ions is plotted versus time (Figure 10), and versus distance from the Peace River "mouth" for the study, or location where it leaves BC (Figure 11).

Appendix 2 also includes the resulting bar plots, over time for all the watersheds, to show evolution of major ions (calcium, magnesium, sodium, bicarbonate, chloride and sulfate).

1.1.2 Water type results

There are nine different water types encountered within the surface water dataset for the PRRD. However, nearly 90% of the samples indicate a calcium bicarbonate (Ca-HCO3) water type. Figure 8 shows a Piper plot classified by watersheds for all the samples where major ions were analyzed. Most of the samples are high in calcium for the cations and high in bicarbonate and sulfate for the anions, with a few samples becoming chloride predominant. A Piper plot was also prepared for each watershed and this information is presented in Appendix 2.

Approximately, 70% of the samples were collected during the low-flow period. There is no obvious difference between low flow and high flow regarding water type as shown in Figure 9. Nevertheless, there are a few samples with high chloride concentration that corresponds to the low flow period. A more detailed representation of the differences between low and high-flow water type results is presented in Appendix 2.

Figure 10 shows the Mekko Chart divided in six time periods in order to explain the evolution of water versus time. The first three groups (samples taking from 1972 to 2000) show a constant water type of calcium bicarbonate. After 2000, there is great variability in water type. For instance, although water type is still calcium bicarbonate, there is an increase in sulfate concentration. In the last time period (2011-2014), in addition to observing an increase in sulfate, we noticed high chloride concentrations for some samples. We acknowledge that a “true” comparison of the water type versus time would have to rely on samples collected from the same locations over time. Unfortunately, such a dataset is very poor in the PRRD; therefore, we are presenting a figure based on available data.

The water type analysis along the Peace River is presented in Figure 11. Water type is predominantly calcium bicarbonate from the mouth (4.5 km) to Williston reservoir (178 km). However, at the mouth of the Peace River, at stations for which we have recent data (2011-2013), we notice an increase in sulfate and chloride. Unfortunately, there is no recent data for stations located upstream of the 4.5 km station.

Spatial distribution of water type for all the watersheds within the PRRD is presented in Figure 12 and Figure 13. Figure 12 shows all the water types and a table summarizing the number of samples that are Ca-HCO3 type over time. In Figure 13 calcium bicarbonate is removed in order to better visualize watersheds that have other water types. It includes a summary table showing a number of samples that fall into a water type group, classified by watershed. The Lower Beatton River and Lower Peace Watersheds have the majority of the water types. Additional information regarding spatial evolution of water type for each watershed is presented in Appendix 2.

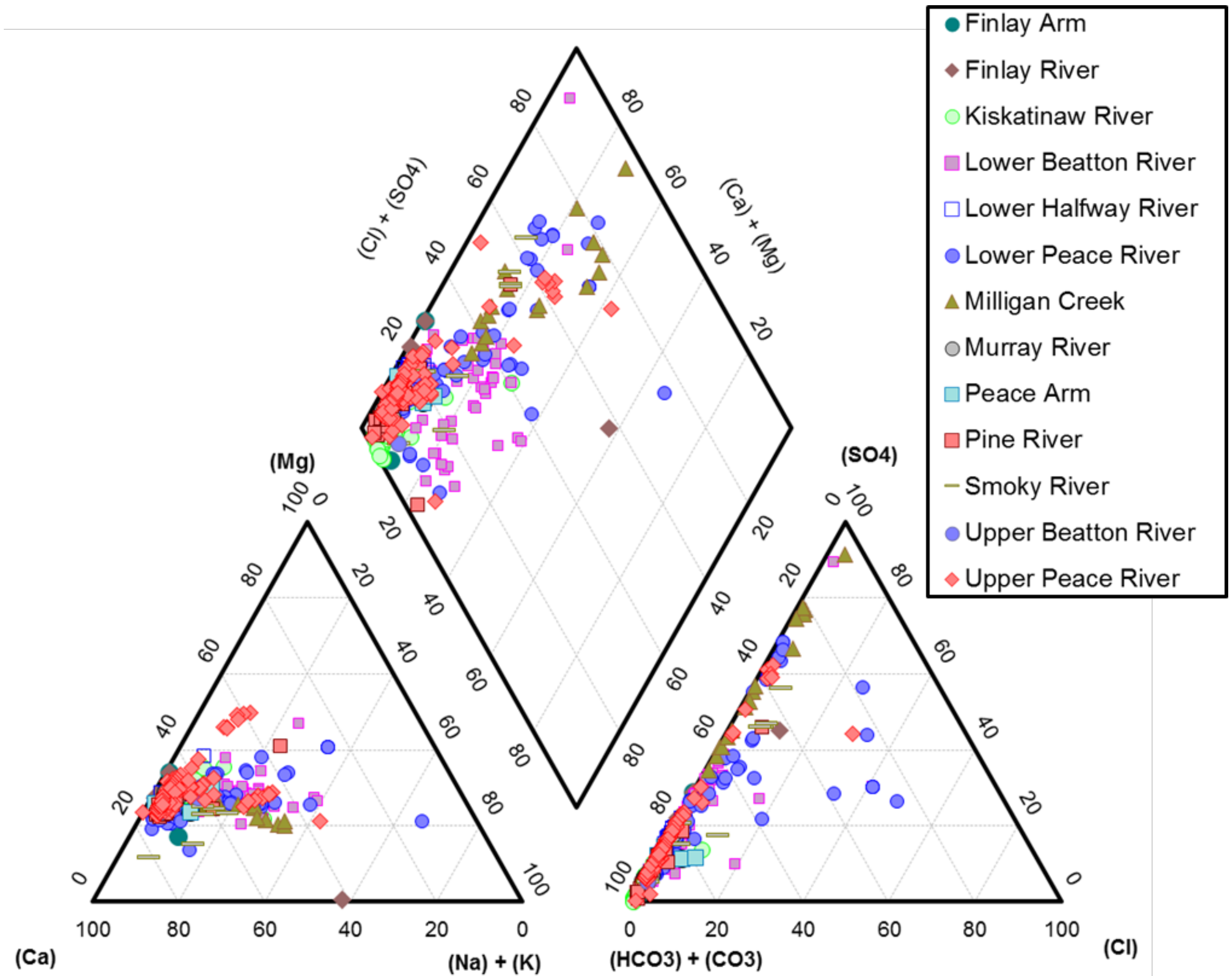


Figure 8. Piper plot for 513 samples where data on the major cations and anions is available.

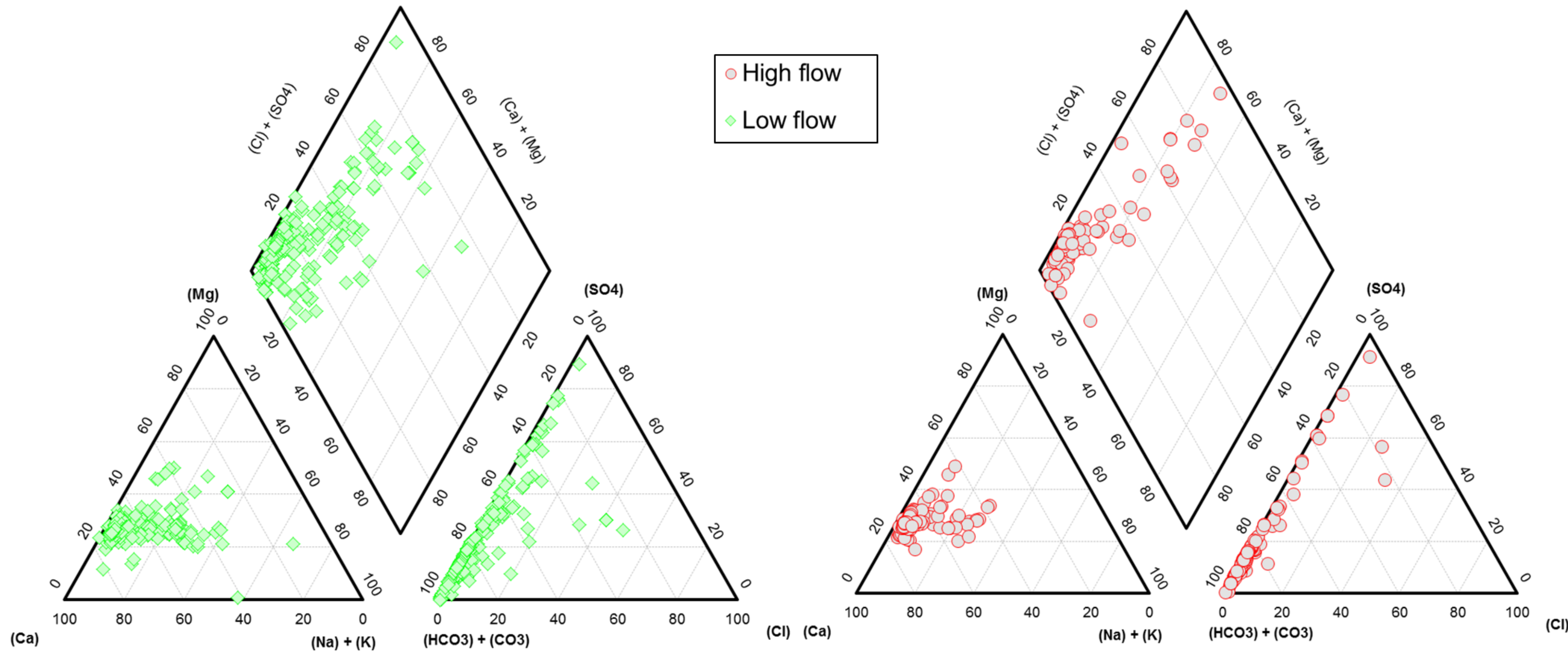
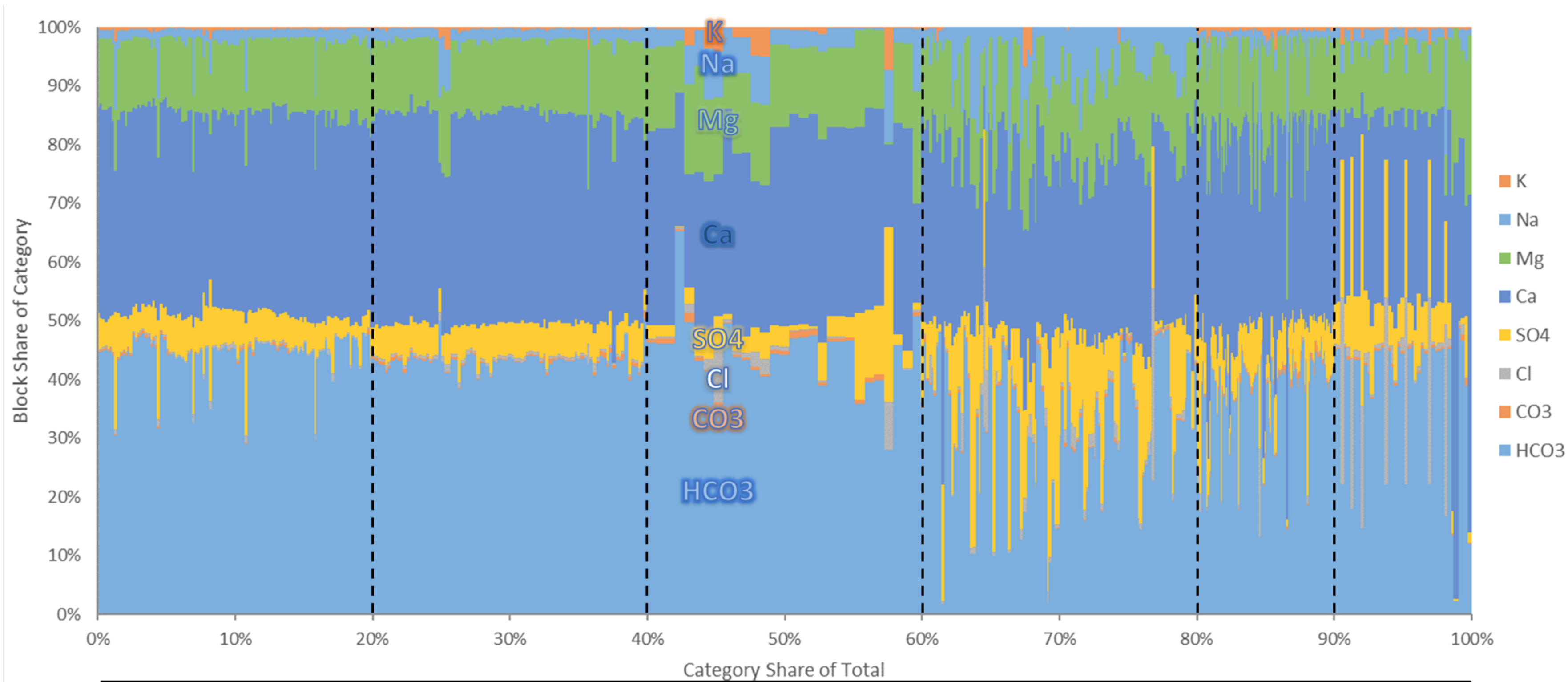
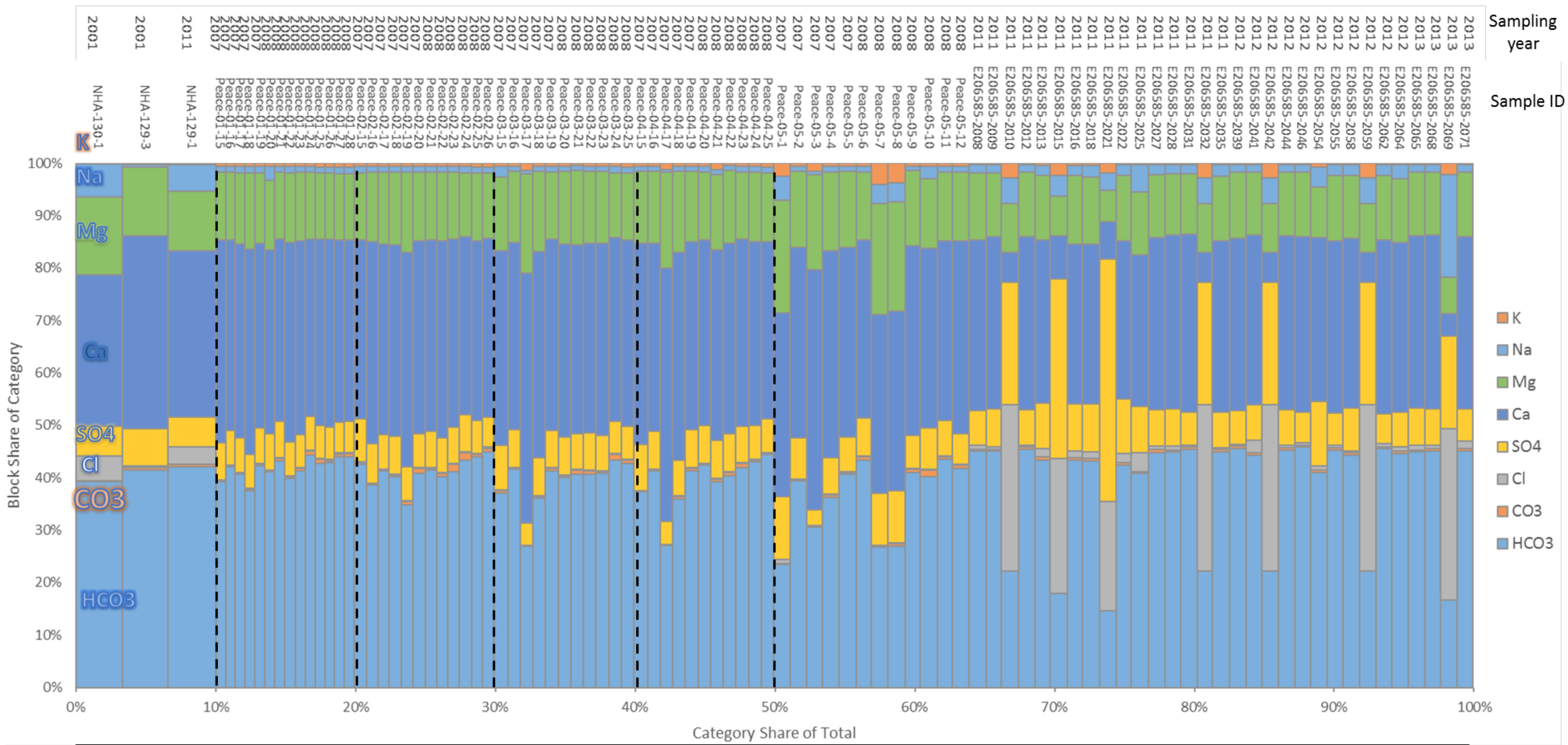


Figure 9. Piper plot for 513 samples classified by high and low flow



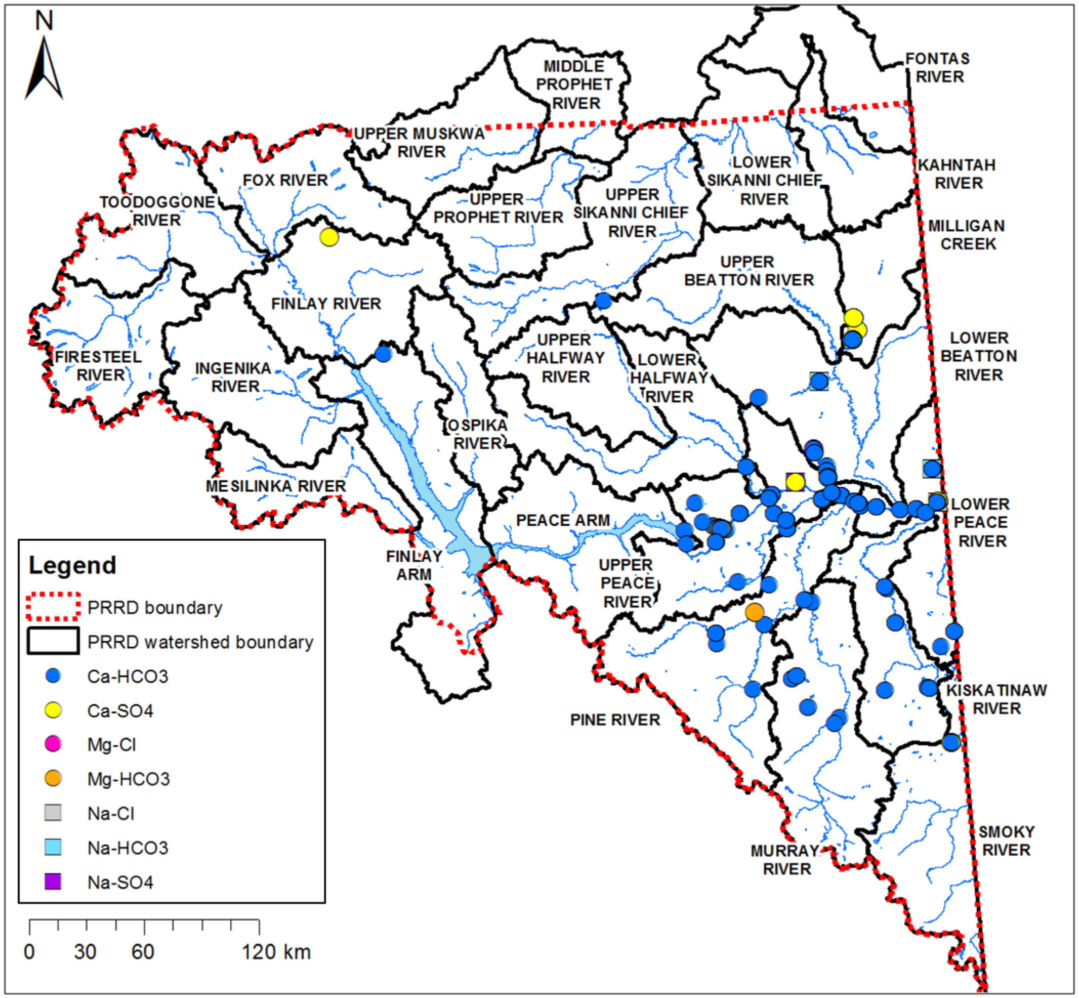
Sampling year	1972-1980	1981-1990	1991-2000	2001-2005	2005-2010	2011-2014
No of Samples	110	87	29	112	134	41

Figure 10. Marimeko chart illustrating change in water type versus time (whole PRRD)



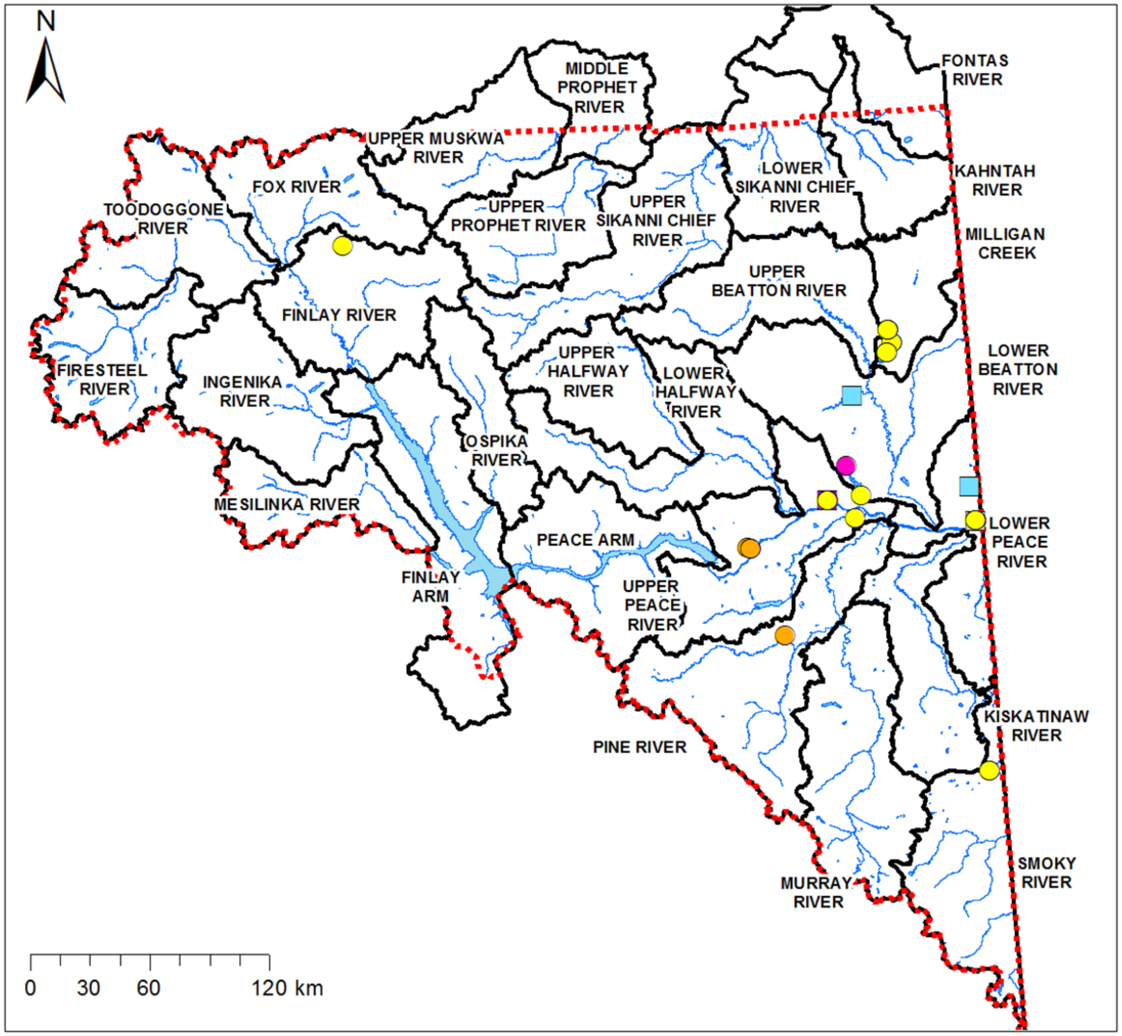
178 Km upstream (Williston Reservoir) Samples 2001-2011	146 Km upstream (Hudson's Hope) Samples 2007-2008	107 Km upstream (Attachie) Samples 2007-2008	67 Km upstream (Grand Haven) Samples 2007-2008	50 Km upstream (Taylor) Samples 2007-2008	4.5 km upstream (at the mouth) Samples 2007-2013

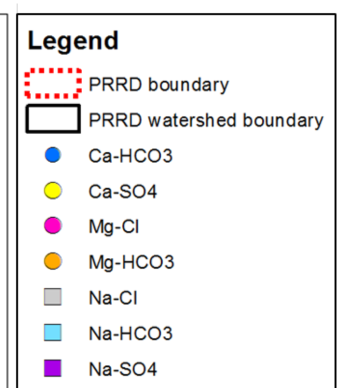
Figure 11. Marimeko chart illustrating change in water type versus distance along the Peace River.



Sampling Year	Ca-HCO3 Water type No of Samples
1972	42
1973	35
1974	14
1976	17
1977	1
1980	1
1984	4
1985	12
1986	27
1987	20
1988	16
1989	7
1990	1
1991	5
1992	1
1994	1
1996	1
1997	10
1998	1
1999	6
2000	2
2001	8
2002	7
2003	33
2004	34
2005	4
2007	48
2008	66
2009	1
2010	2
2011	14
2012	11
2013	3
2014	5
Total	**460**

Figure 12. Surface water type with summary table of number of samples over time that corresponds to Calcium-Bicarbonate.





Watershed	No of samples						
	Ca-HCO3	Ca-SO4	Mg-Cl	Mg-HCO3	Na-Cl	Na-HCO3	Na-SO4
FINLAY ARM	1						
FINLAY RIVER	3	1					
KISKATINAW RIVER	36						
LOWER BEATTON RIVER	42	1	1			1	
LOWER HALFWAY RIVER	11						
LOWER PEACE RIVER	195	9	4		1	1	
MILLIGAN CREEK	6	11					
MURRAY RIVER	12						
PEACE ARM	3						
PINE RIVER	26			1			
SMOKY RIVER	5	2					
UPPER BEATTON RIVER	1						
UPPER PEACE RIVER	119	7		5			1
Total samples	**460**	**31**	**5**	**6**	**1**	**2**	**1**

Figure 13. Surface water type except Calcium-Bicarbonate type.

1.2 Comparison with Water quality guidelines

1.2.1 Comparison with Federal guidelines

The most stringent thresholds are defined in the guideline for the protection of Aquatic Life followed by Drinking Water, Irrigation, and Livestock Watering. The recreational guideline is not included since there is a threshold for only three parameters (fecal coliforms, suspended solids and turbidity) and this guideline is less stringent than the other guidelines. Figure 14 displays the number of samples exceeding the federal guidelines for 32 parameters. In addition, Figure 15 shows the percentage of exceedances in comparison to the total number of samples analyzed for these parameters. There are 9 parameters, all of them total metals, that indicate a higher percentage of exceedances: Aluminum, Arsenic, Cadmium, Copper, Iron, Lead, Mercury, Molybdenum, Nickel, Selenium, and Silver.

Although presenting data as number of samples exceeding a guideline, such as in Figure 14 and Figure 15, is useful to identify which parameter did not meet the guidelines, it does not allow the comparison between samples as a whole. Therefore, GW Solutions elected to use a water quality index (CCME-WQI) in order to better represent water quality. A water quality index (WQI) allows integrating three different factors: F1 (scope), F2 (frequency) and F3 (amplitude). The first factor relates to the number of failed variables (parameters) compared to the total number of analyzed parameters that have a guideline value. The second factor incorporates the number of exceedances compared to the total number of tests carried out in all the samples. Finally, the third factor includes the percentage at which the exceedance occurred compared to the guideline value. There are five WQI categories to describe the water quality: excellent (WQI 95-100), good (WQI 80-94), fair (WQI 65-79), marginal (WQI 45-64), and poor (WQI 0-44).

This method was developed by the Canadian Council of Environmental Ministers (CCME), and the rational and details of calculation can be found in Appendix 3.

The 19 parameters selected to calculate the WQI are listed in Table 7. The WQI was calculated using the Aquatic Life - Long Term guideline because it is the most stringent and it generally applies, by default for surface water quality. As described above, we have classified the data in several time periods. Figure 16 shows the water quality index for samples taken before and after 2001. In general, the WQI is good to excellent at the headwaters of the Murray, Pine and Kiskatinaw River watersheds. However, the discharge of the majority of the watersheds shows a slightly lower rating of the WQI, indicating a degradation of water quality as water flows from the headwaters to the mouth of the watersheds. In addition, there is a change in WQI between the two time periods (before and after 2001). For example, WQI at the mouth of the Murray River watershed is excellent for samples taken before 2001 and WQI becomes fair for samples taken after 2001.

The results for this analysis are presented for all the watersheds in Appendix 4. The database and the macros generated allow the calculation and visualisation of any time period and areas.

Estimating the change in WQI is useful to determine whether water quality has degraded, stayed the same, or improved over time. The change in WQI was calculated considering five WQI estimated for different time periods: samples taken between 1) 1955 and 1990, 2) 1991 and 2000, 3) 2001 and 2005, 4) 2006 and 2010 and 5) 2011-2014. A positive, negative, and constant WQI trend will indicate an increase (improvement), drop (worsening) or no change of the water quality, respectively. Figure 17 displays the WQI trends for the PRRD. There are a few stations where the water quality remains stable over time. Data suggests the water quality has degraded over time along the Peace River. However, each watershed exhibits different behaviours. Appendix 4 presents a more detailed data interpretation for every watershed including Water Quality Index trend and WQI classes.

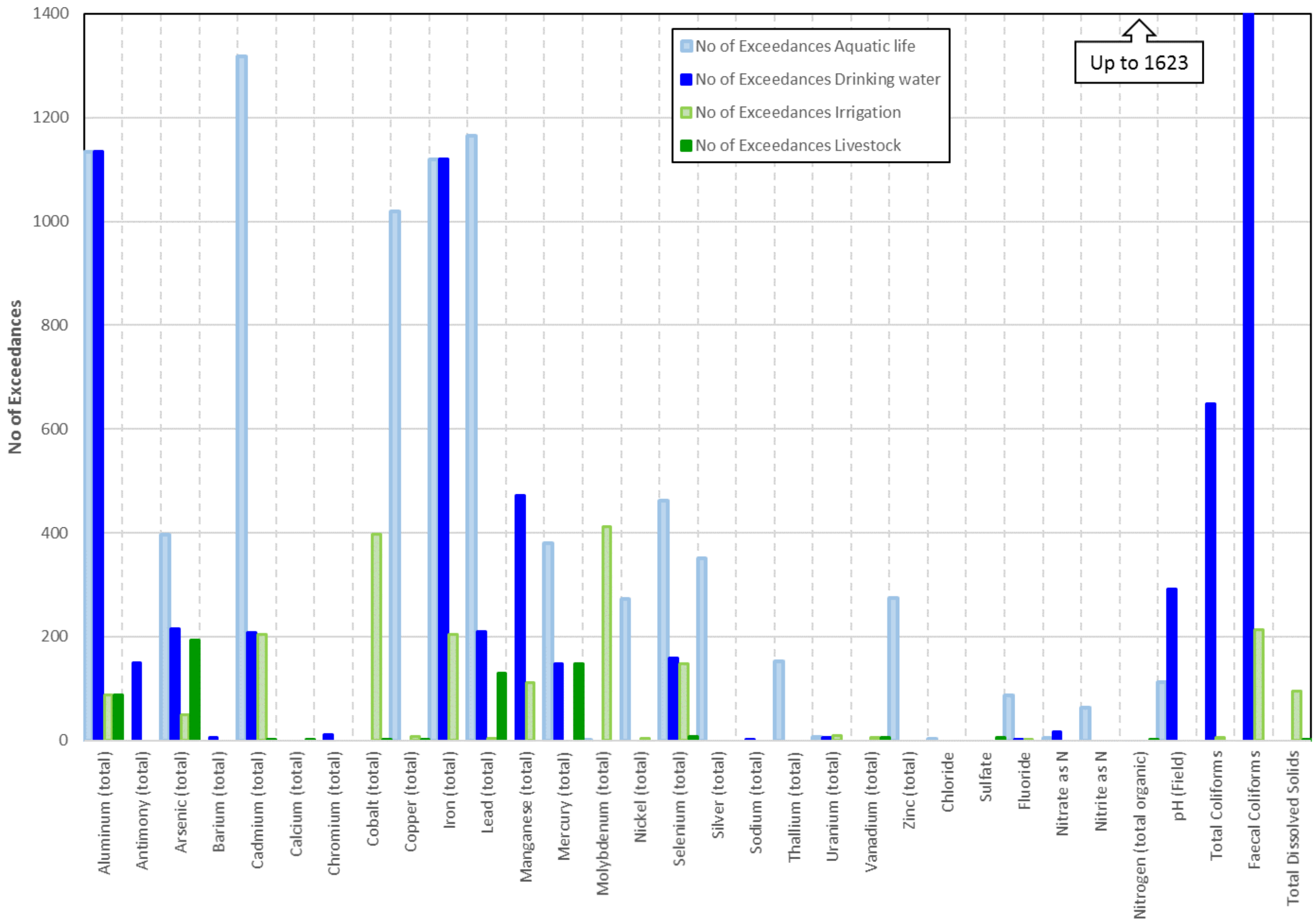


Figure 14. Number of samples exceeding federal guidelines

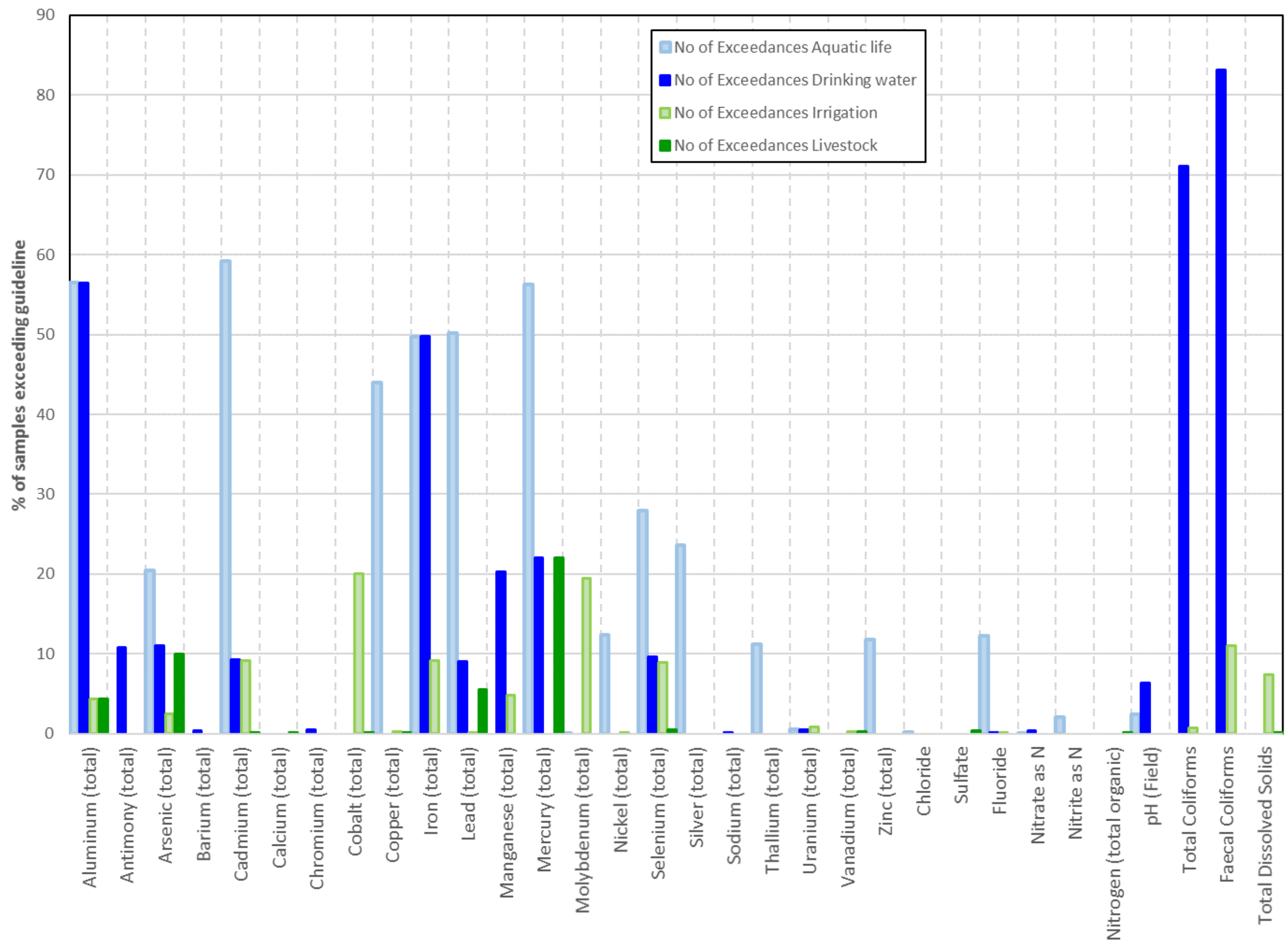


Figure 15. Percentage of samples exceeding federal guidelines compared to the total number of analyzed samples

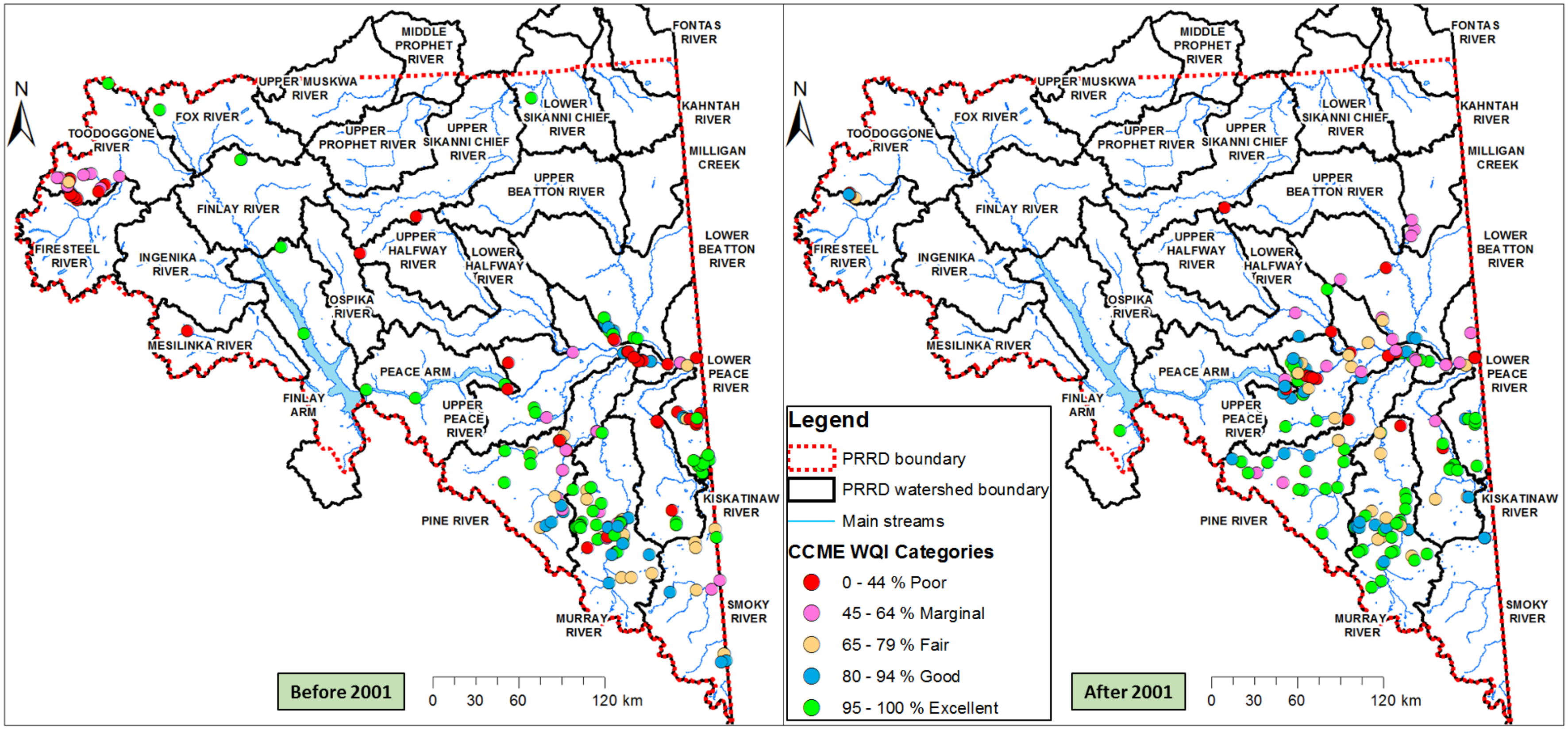


Figure 16. CCME Long Term Aquatic Life Water Quality Index (WQI) for samples taken before 2001 and samples taken after 2001

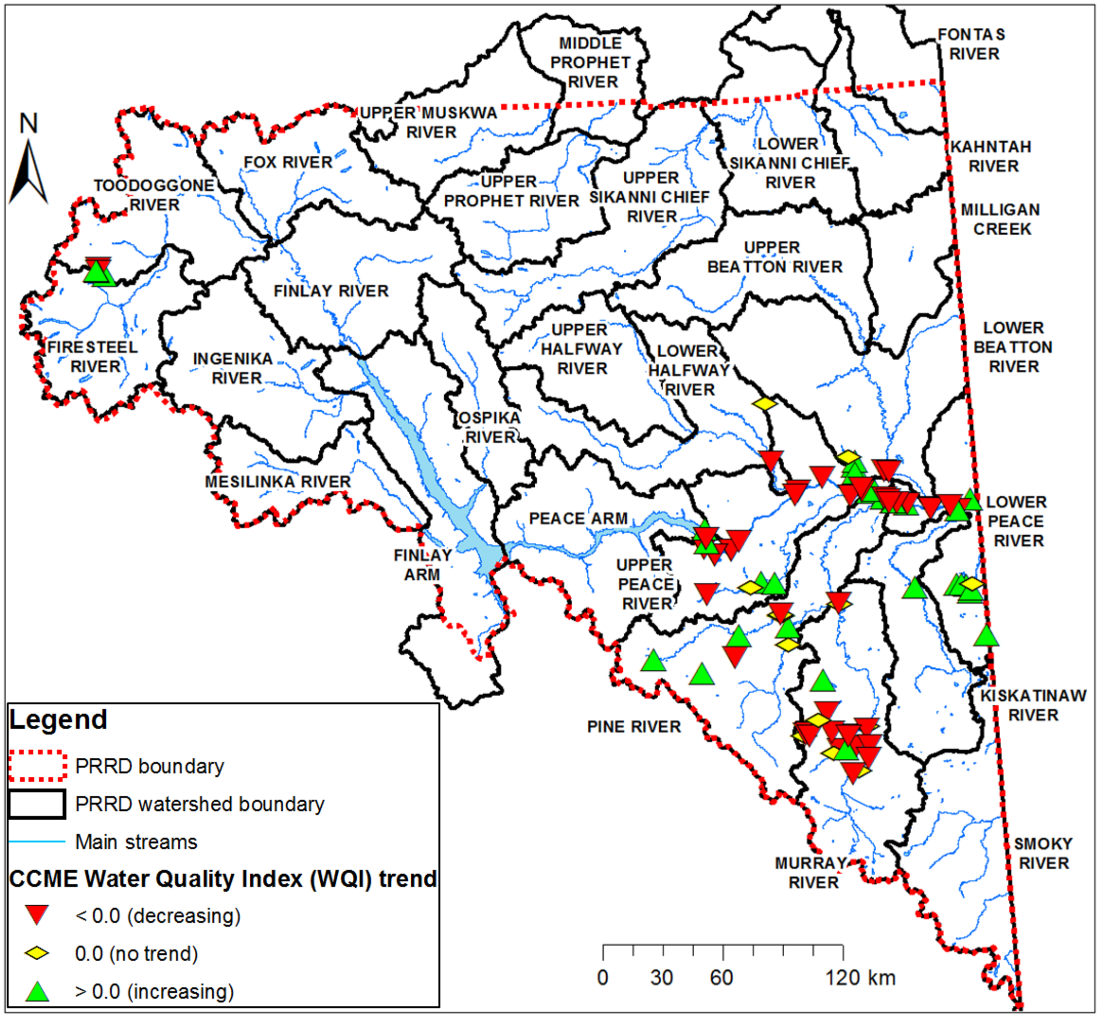


Figure 17. Water quality index trend for all the stations with available data within the PRRD – referring to CCME Long Term Aquatic Life guideline

Table 7. Parameters and CCME Aquatic Life objectives considered for the WQI calculation

No	Parameter	Unit	CCME Aquatic Life objective (Long term)	Comment
1	Aluminum (total)	µg/L	100	Depends on pH. 100 µg/L for pH>6.5
2	Arsenic (total)	µg/L	5	
3	Cadmium (total)	µg/L	0.09	
4	Copper (total)	µg/L	2	Depends on Hardness. 2 µg/L for Unknown hardness
5	Iron (total)	µg/L	300	
6	Lead (total)	µg/L	1	Depends on Hardness. 1 µg/L for Unknown hardness
7	Mercury (total)	µg/L	0.026	
8	Molybdenum (total)	µg/L	73	
9	Nickel (total)	µg/L	25	Depends on Hardness. 25 µg/L for Unknown hardness
10	Selenium (total)	µg/L	1	
11	Silver (total)	µg/L	0.1	
12	Thallium (total)	µg/L	0.8	
13	Uranium (total)	µg/L	15	
14	Zinc (total)	µg/L	30	
15	Chloride	µg/L	120000	
16	Fluoride	µg/L	120	
17	Nitrate as N	µg/L-N	13000	
18	Nitrite as N	µg/L-N	60	
19	pH (Field)		6.5-9.0	

1.2.2 Comparison with Provincial guidelines

Figure 18 shows a summary of number of exceedances per analysed parameters. The guideline for protecting freshwater aquatic life is the most stringent. Of the 14 parameters that exceed the thresholds, dissolved cadmium, total iron, total selenium and total phosphorous have the highest number of exceedances. Additionally, Figure 19 presents the percentage of exceedance (number of samples exceeding threshold divided by number of samples analysed). Dissolved cadmium has the highest exceedance percentage (78% of the samples exceeds guideline), followed by total phosphorous (33%), total iron (28%) and total boron (14%).

Although WQI calculations are similar using both the CCME and BCMOE approach, the BCMOE based rating and range of Water Quality Index are slightly different due to the difference in thresholds compared to the CCME, as summarized in Table 8. The BC aquatic life guideline is more stringent than the CCME aquatic life guideline. Water Quality Index values were calculated for the entire PRRD using 20 objectives from BCMOE Aquatic Life (Acute) guideline as summarized in Table 9. In addition, two time periods were considered: up to 2000 and starting in 2001 to present.

Figure 20 displays the results considering the scenarios described above. Most of the water quality samples indicate a poor quality for both illustrated time periods.

The Water quality index trend was also calculated considering the same time periods as for the CCME WQI trend. Figure 21 displays WQI trends for stations for which a trend could be estimated. In general, the results are very similar to the WQI trend using CCME aquatic life guideline presented in Figure 17. For example, we observe decreasing trends (the water quality is getting worse) along the Peace River and for most stations within the Murray River Watershed. Appendix 5 presents the results of the WQI analysis by watersheds.

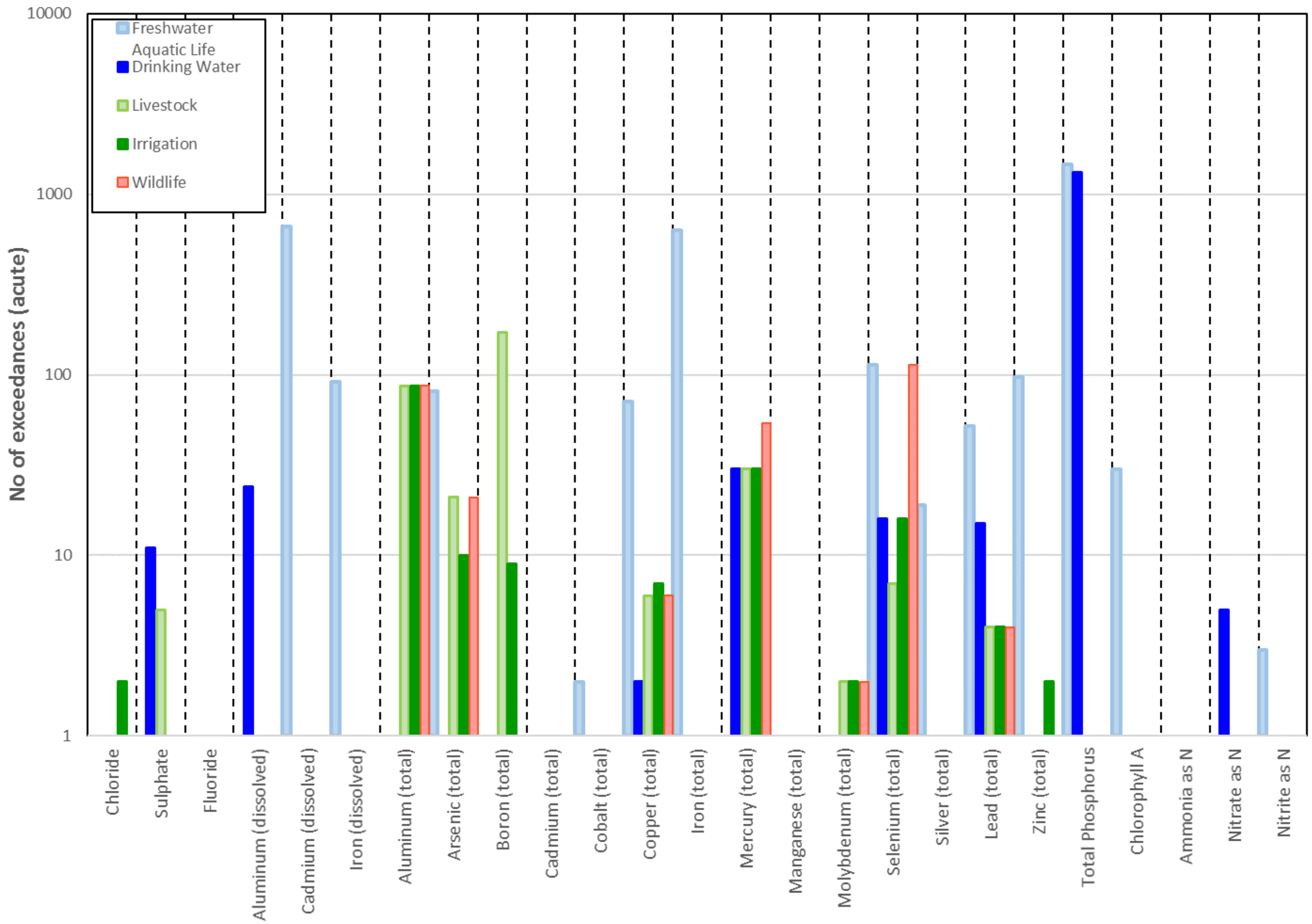


Figure 18. PRRD Number of samples exceeding BC provincial guidelines

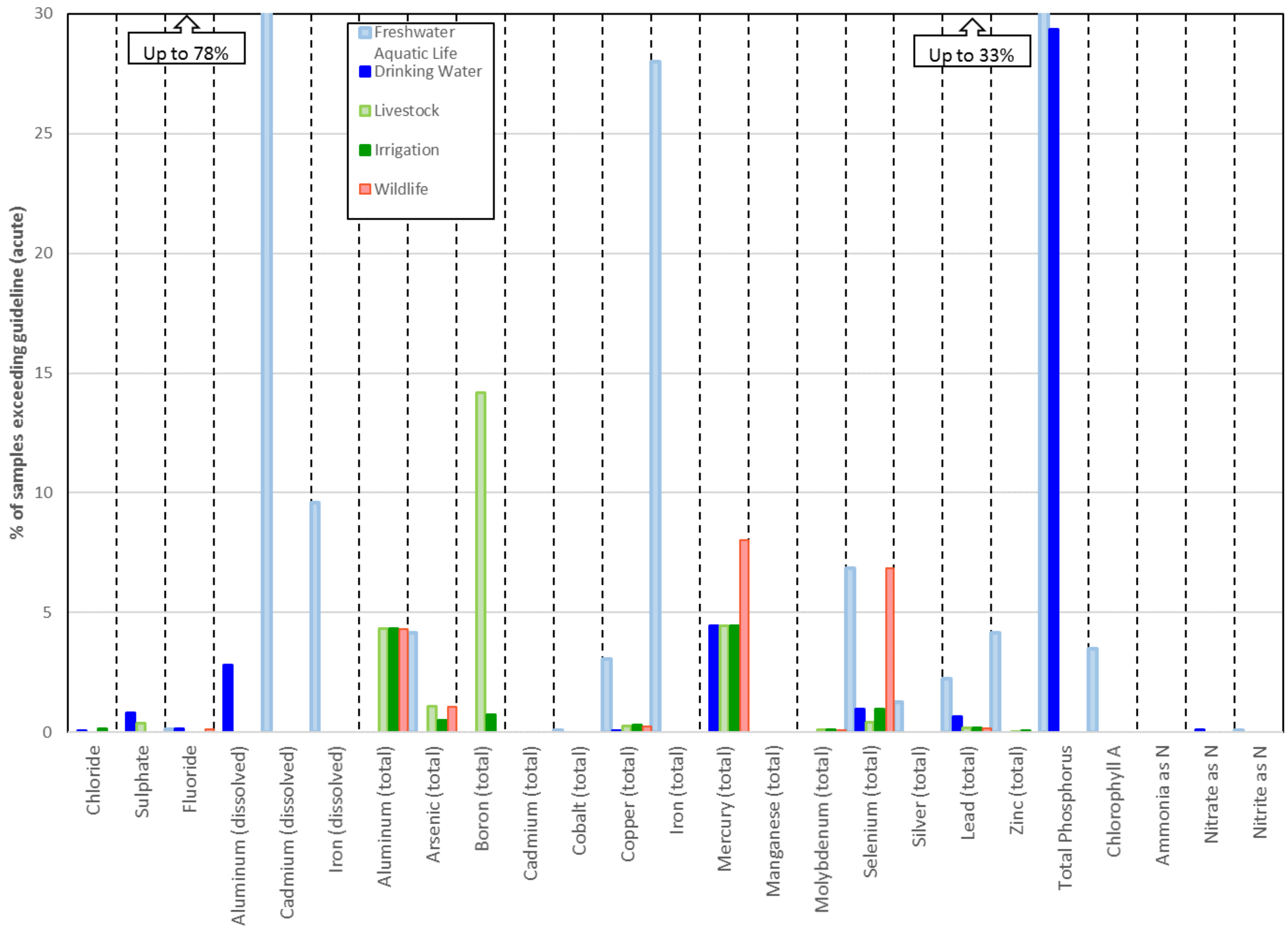


Figure 19. PRRD Percentage of samples exceeding BC provincial guidelines compared to the total number of samples

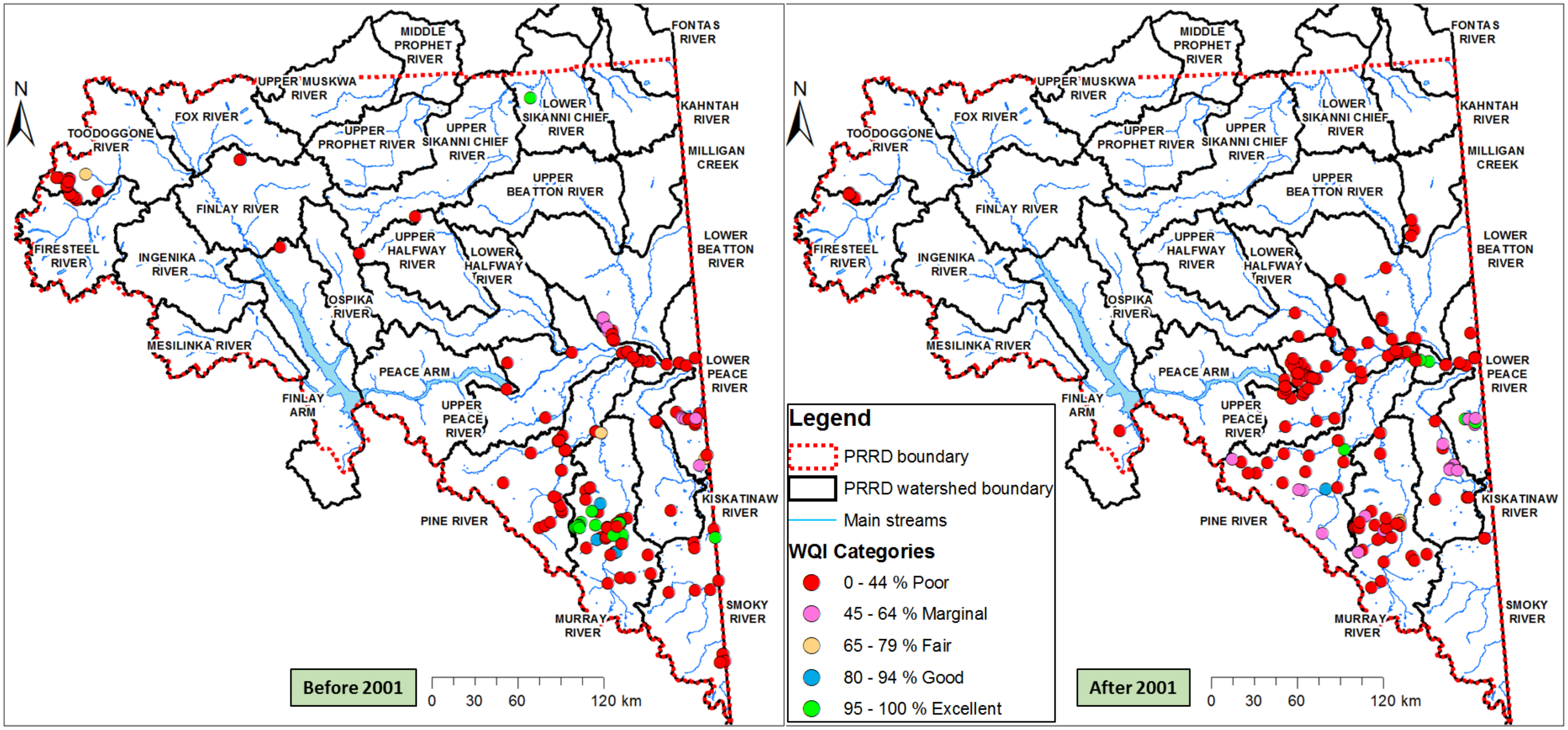


Figure 20. Water Quality Index (WQI) – referring to BCMOE Acute Aquatic Life guideline - for samples collected before 2001 and samples collected after 2001

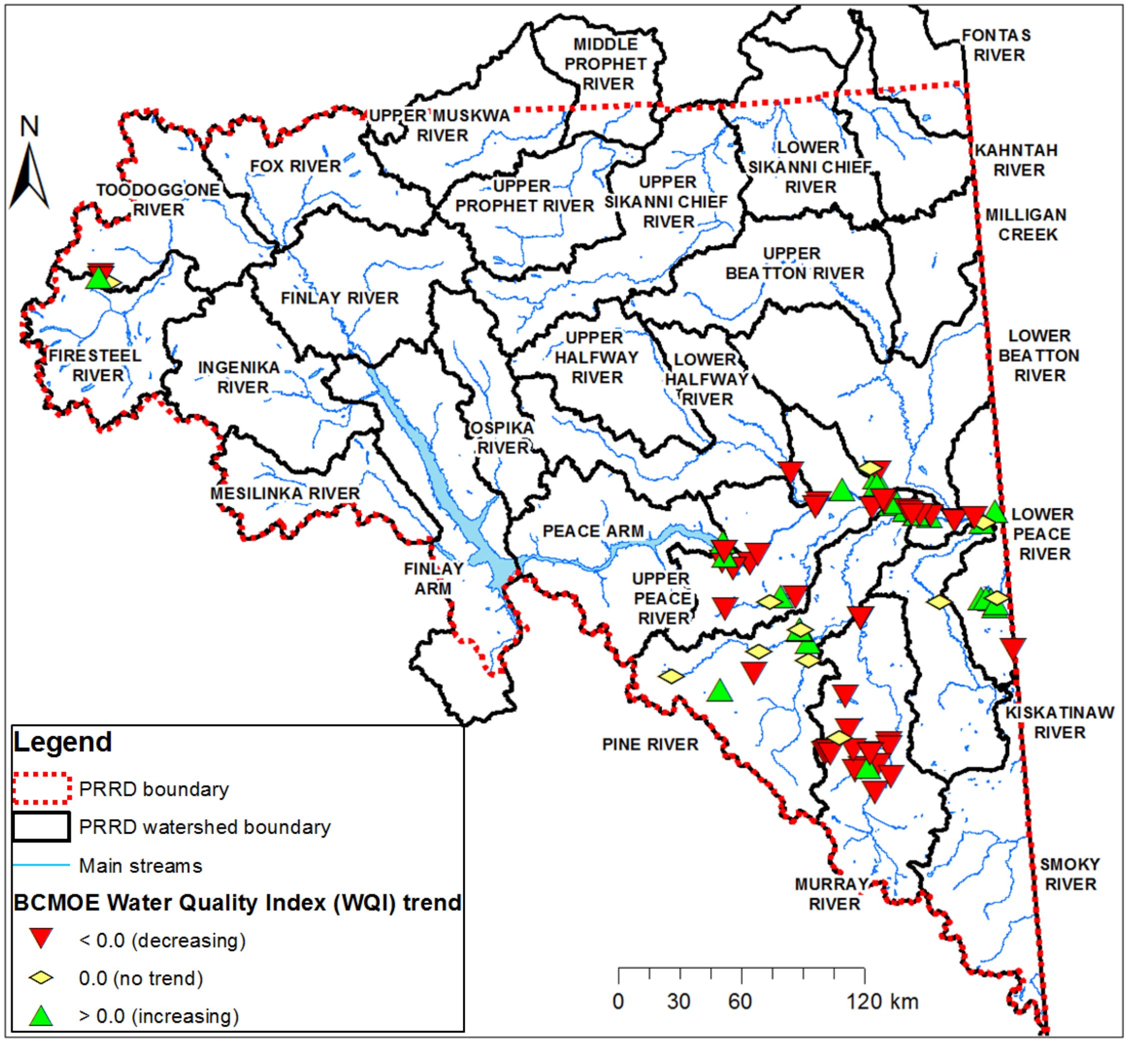


Figure 21. Water quality index trend for the PRRD – referring to BCMOE Acute Aquatic Life guideline

Table 8. Water Quality Index rating and range for both CCME and BCMOE WQI

BCMoE Rating	BCMoE Water Quality Index Range	CCME Rating	CCME Water Quality Index Range
Excellent	97-100	Excellent	95-100
Good	83-96	Good	80-94
Fair	57-82	Fair	65-79
Borderline	41-56	Marginal	45-64
Poor	0-40	Poor	0-44

Table 9. Parameters and BCMOE Aquatic Life (acute) objectives considered for the WQI calculation

No	Parameter	Unit	Aquatic Life Freshwater (Acute) Objective	Comments
1	Aluminum (dissolved)	ug/L		pH dependent
2	Cadmium (dissolved)	ug/L		Hardness dependent
3	Iron (dissolved)	ug/L	350	
4	Arsenic (total)	ug/L	5	
5	Boron (total)	ug/L	1200	
6	Cobalt (total)	ug/L	110	
7	Copper (total)	ug/L		Hardness dependent
8	Iron (total)	ug/L	1000	
9	Manganese (total)	ug/L		Hardness dependent
10	Molybdenum (total)	ug/L	2000	
11	Selenium (total)	ug/L	2	
12	Silver (total)	ug/L	0.1	

No	Parameter	Unit	Aquatic Life Freshwater (Acute) Objective	Comments
13	Lead (total)	ug/L		Hardness dependent
14	Zinc (total)	ug/L		Hardness dependent
15	Chloride	ug/L	600000	
16	Fluoride	ug/L		Hardness dependent
17	Total Phosphorus	ug/L	15	For lakes Range between 5-15 ug/L
18	Nitrate as N	ug-N/L	32800	
19	Nitrite as N	ug-N/L	60	
20	pH		6.5-9.0	

1.3 Change in water chemistry over time

1.3.1 Scatter charts

Scatter plots for all the stations were created using a built-in excel macro. The spreadsheet allows us to choose the watershed, parameter group (i.e. major ions), parameters, flow season (low and high), and the time period. In addition, the scatter plots include the BCMOE guidelines for reference. Figure 22 shows an example of a scatter plot, generated using the built-in macro, for selenium (total) at station E206585 located at the mouth of the Peace River. Appendix 6 presents the scatter plots for all the stations and parameters considered within this analysis.

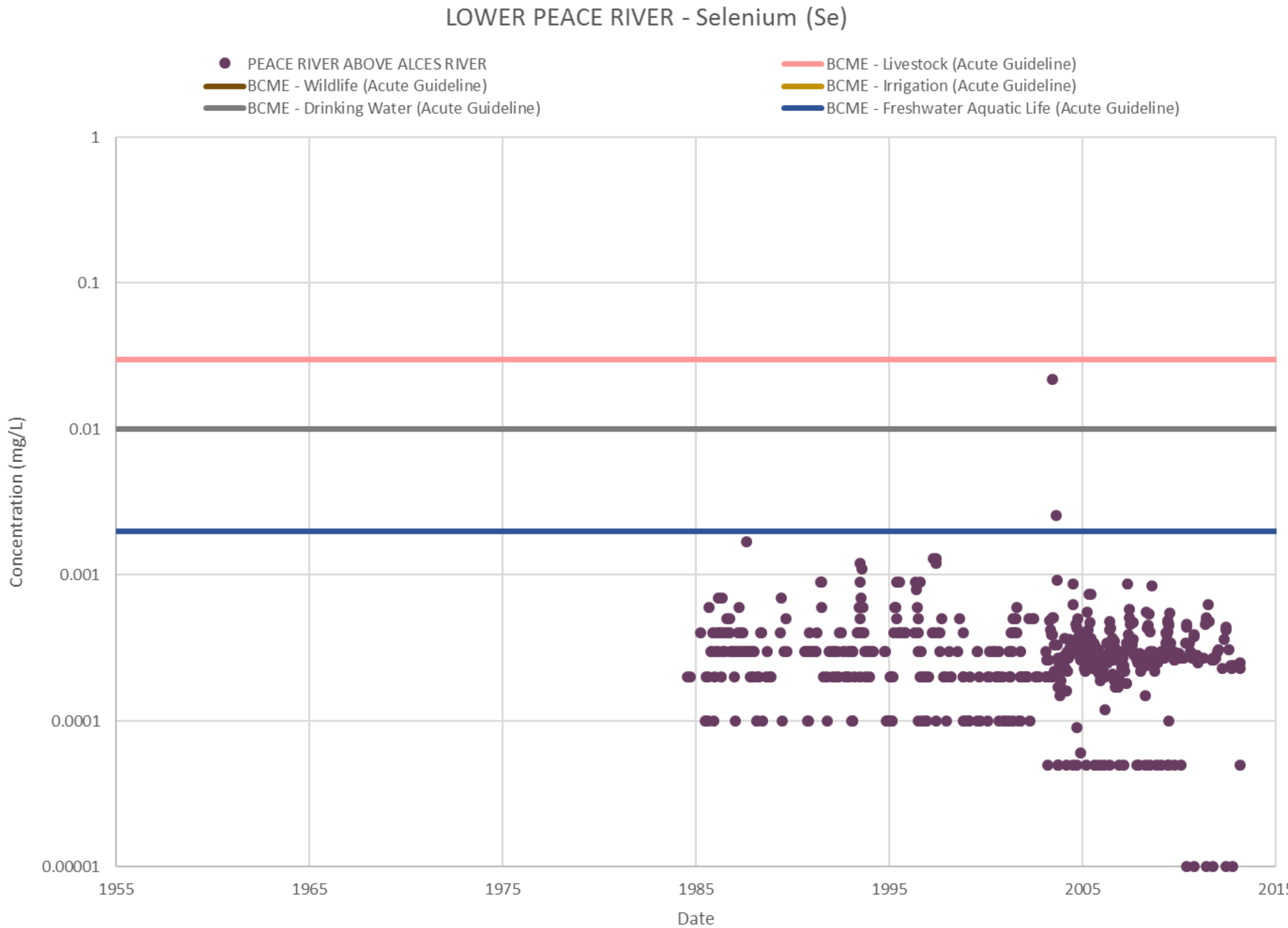


Figure 22. Example of scatter plot for Selenium (total) for the Lower Peace River Watershed station E206585 (Peace River above Alces River)

1.3.2 Trend analysis

Four methods were used to estimate the water quality trend: 1) Mann-Kendal, 2) Seasonal Mann-Kendal, 3) Sen's test and 4) Linear regression. Two time frames were considered for the trend analysis; 1) for samples collected prior 2001 and 2) for samples collected after 2001. In addition, only stations with five years of data with at least 10 samples were considered. Different results were obtained using the four methodologies. However, a trend result was assigned to a parameter only if at least three of the four methods used provided the same answer. Otherwise, the trend results were qualified ambiguous.

There are 57 stations providing data prior to 2001, for which trend tests can be carried out. For samples collected after 2001, only 5 stations had enough data to run a trend analysis. Results of the trend analysis are presented in Appendix 7. An example of the trend result is presented in Figure 23 where it shows the decreasing trend of Cadmium (total) along the Peace River. There is only one sample showing a trend after 2001, because of the lack of data to comply with the constraint to run a trend test (at least 10 samples and five years of data).

Further trend analysis was carried out for Station ID E206585 since it is located at the mouth of the Peace River and provides the largest data set. The trend results for some of the parameters (lithium, barium, selenium, thallium, chloride, sodium, potassium, sulphate, pH and specific conductance) are included in Appendix 7. Examples of the results are presented in Figure 24 and Figure 25. The first Figure shows the variation of Sodium concentration, grouped by blocks of 5-year periods, on a monthly basis. Sodium concentration shows larger variability in the last two sampling periods (2006-2010 and 2011-2014). In addition, sodium concentration is slightly influenced by the flow pattern (high and low flow). The second Figure 25 corroborates the larger variability of sodium concentration for samples taken after 2009. Unfortunately, there is a lack of data between 1995 and 2008 to properly assess the sodium concentration in this period.

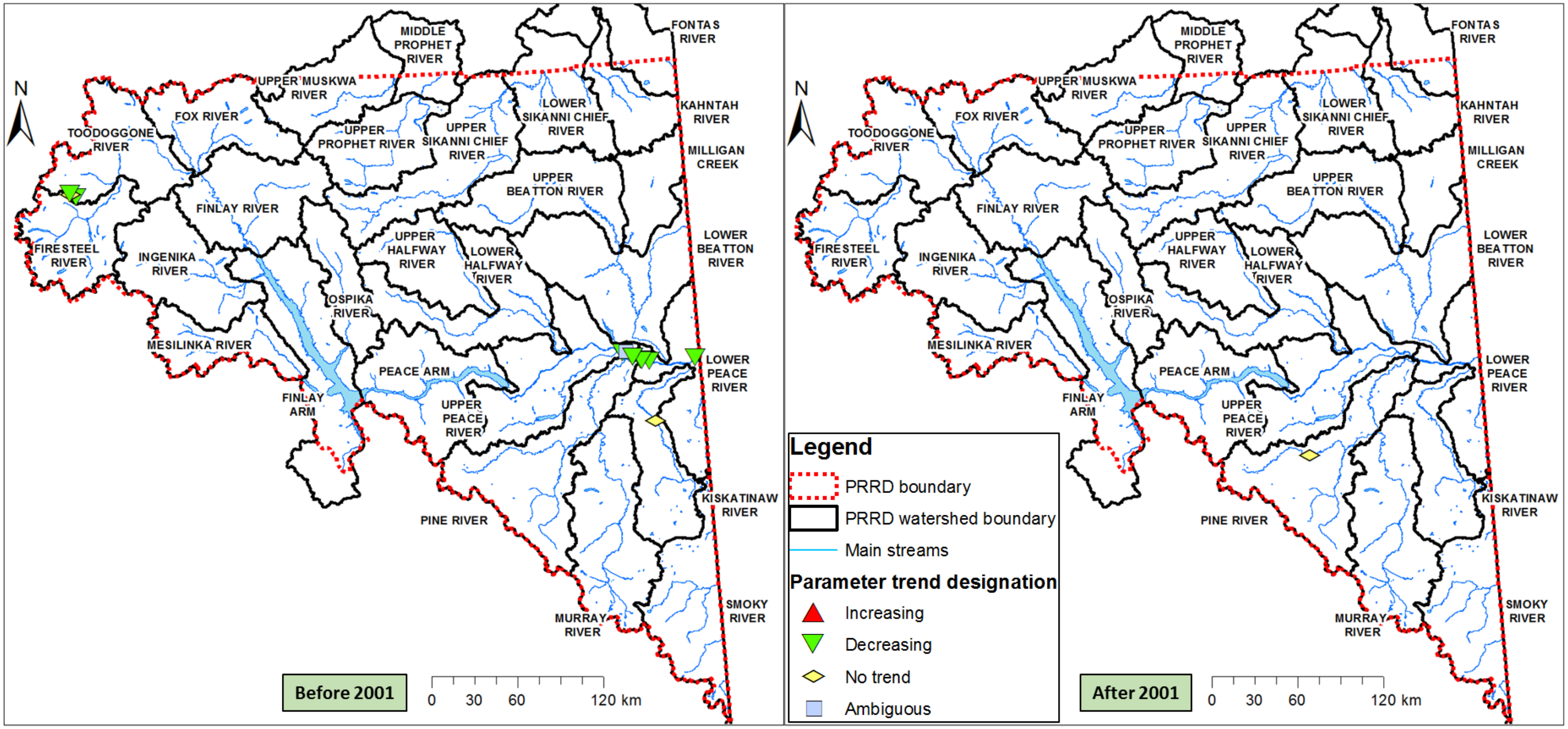


Figure 23. Example of trend analysis results for Cadmium (total)

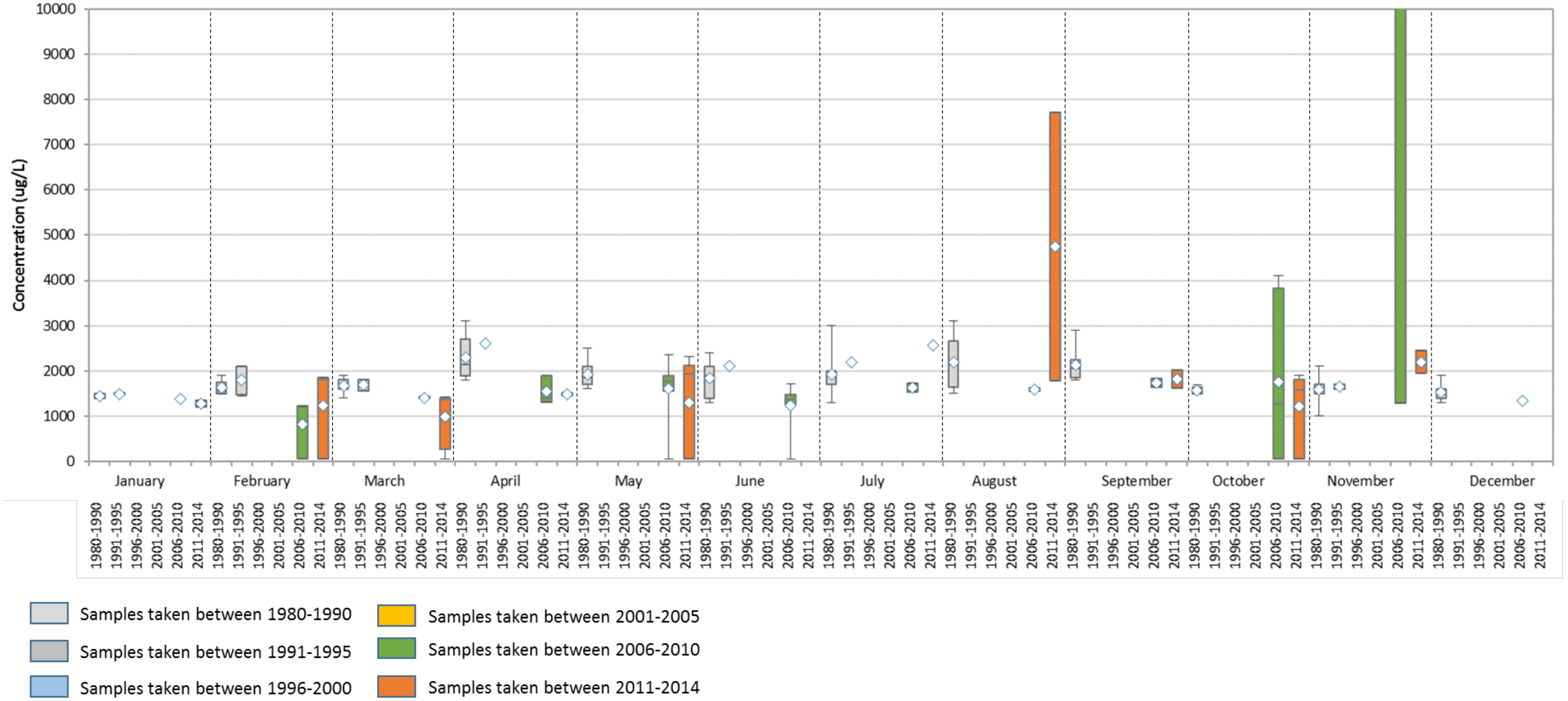


Figure 24. Graphical trend analysis for Sodium at Station E206585

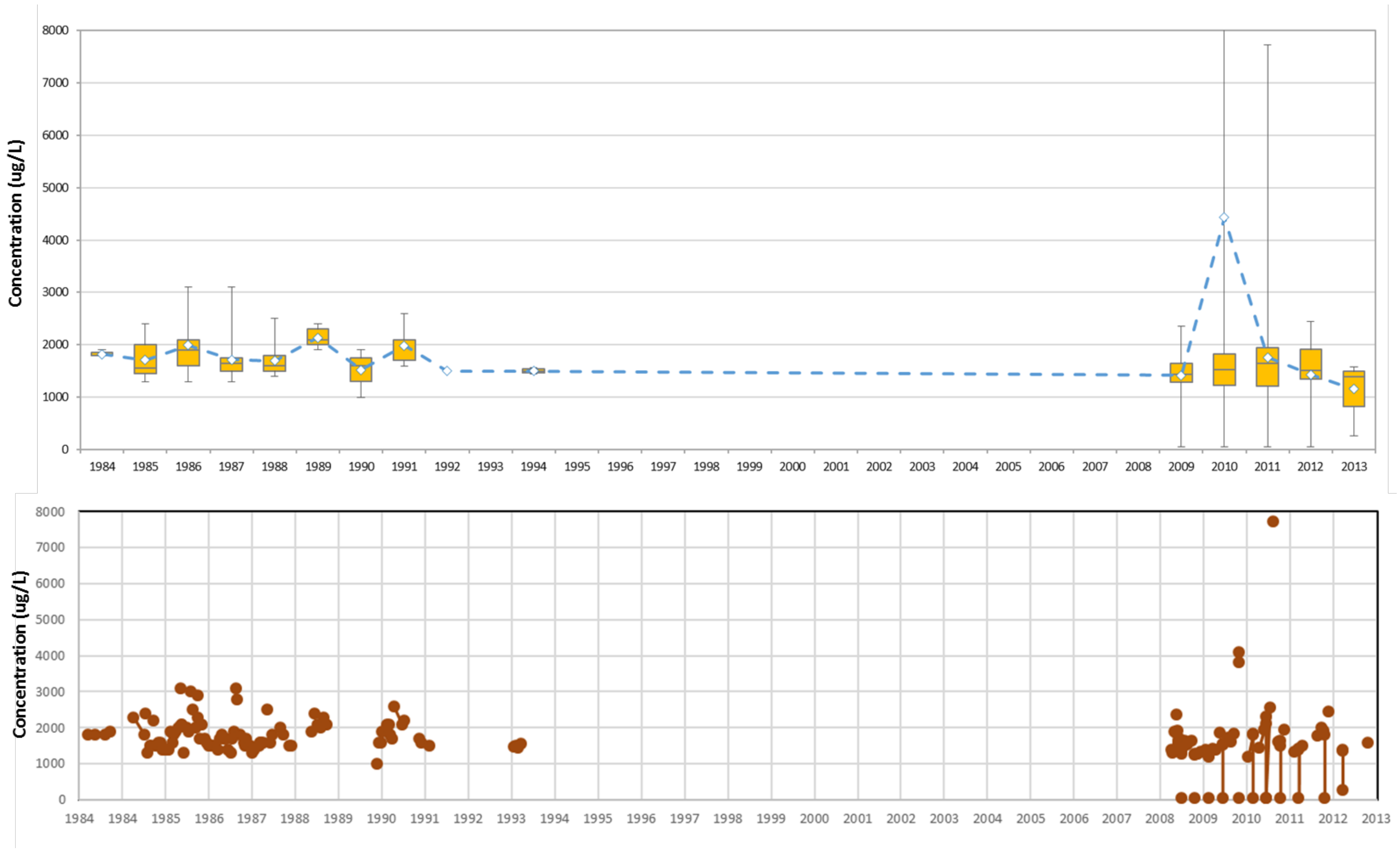


Figure 25. Sodium concentration change over time at Station E206585

2 Groundwater quality analysis

2.1 Water type determination

2.1.1 Water type analysis

Figure 26 is the piper plot for all the groundwater samples taken within the PRRD. Wells in surficial aquifers are mainly calcium/magnesium – bicarbonate/ sulphate type and bedrock wells are predominantly sodium/calcium – bicarbonate/sulphate type.

Figure 27 displays the piper diagram for wells in surficial aquifers grouped by mapped aquifers. There are 12 aquifers with water type assignation. Three aquifers have sodium bicarbonate/sulphate dominant water type and the remaining are calcium bicarbonate/sulphate water type. We note that the samples that indicate higher chloride proportion correspond to dug wells with water tables shallower than 5 m, aquifer 440 (Hudson's Hope area), and one well located in Chetwynd. We also note that in 2002, water type for the supply wells for Fort St. John (completed within Aquifer 442 IA (12)) became calcium sulphate. This seems to represent a shift from the calcium bicarbonate type they previously had. Additional information on water type can be found in Appendix 8.

Figure 28 presents the piper plot for bedrock wells grouped by mapped aquifers. A water type has been assigned to 16 mapped aquifers. Nine aquifers have sodium bicarbonate/sulphate water type dominant water and seven mapped aquifers are calcium bicarbonate/sulphate water type. For instance, aquifer 627 IIIB (10) is sodium bicarbonate type whereas 441 IIIB (10) is calcium bicarbonate type. Appendix 8 presents separate piper plots for all the mapped aquifers.

Piper diagram for samples taken from springs are presented in Figure 29. The water type is very similar to water from surficial aquifers, predominantly calcium bicarbonate/sulphate. A few samples are sodium bicarbonate/sulphate and correspond to samples collected after 2013.

2.1.2 Temporal and spatial change of water type

Figure 30 displays the piper diagram for the wells in surficial aquifers grouped by sampling period. In general, the groundwater type is calcium bicarbonate (low sodium ratio) for samples taken before 2001. Between 2001-2010 the sodium proportion increases, but the water type still remains calcium bicarbonate except for the Fort St. John water supply wells, which show calcium sulphate in 2002. Nevertheless, samples collected between 2011 and 2015 show a range of water type including calcium/sodium - bicarbonate/ sulphate. This evolution over time, for wells in surficial aquifers, is also presented in the Marimekko chart (Figure 31).

Figure 32 depicts the piper plot for the bedrock wells classified by sampling period. Most of the samples were taken between 2011 and 2015. Figure 34 also shows the evolution of water type in a Marimekko chart. Figure 33 presents an example of piper plot evolution for aquifer 591 IIIC (12). The water type is predominantly sodium bicarbonate for samples collected between 1981 and 2000. However, samples taken in 2011-2015 show a wide range of water type.

Figure 35 shows a bar plot over time, for all the grouped bedrock wells, showing three major cations and three major anions in meq/L. Samples taken after 2011 show a higher level of mineralisation. Partly, this is due to the larger number of samples collected after 2011 from different locations across the PRRD where variability is expected from one place to another.

A piper plot describing the composition of the samples collected from the springs (grouped by sampling periods) and showing water composition over time is presented in Figure 36. Samples taken before 2005 predominantly indicate a calcium bicarbonate/sulphate water type. We observe that the springs sampled after 2011 present a higher proportion for sodium. However, we note that to properly comment on a change versus time, we would need data from the same springs over different sampling events. For the existing dataset, data available before 2011 comes from six different springs. Data after 2011 comes from 16 springs from which only two springs have been sampled before 2011.

Additional information and maps about the changes in water type are included in Appendix 8.

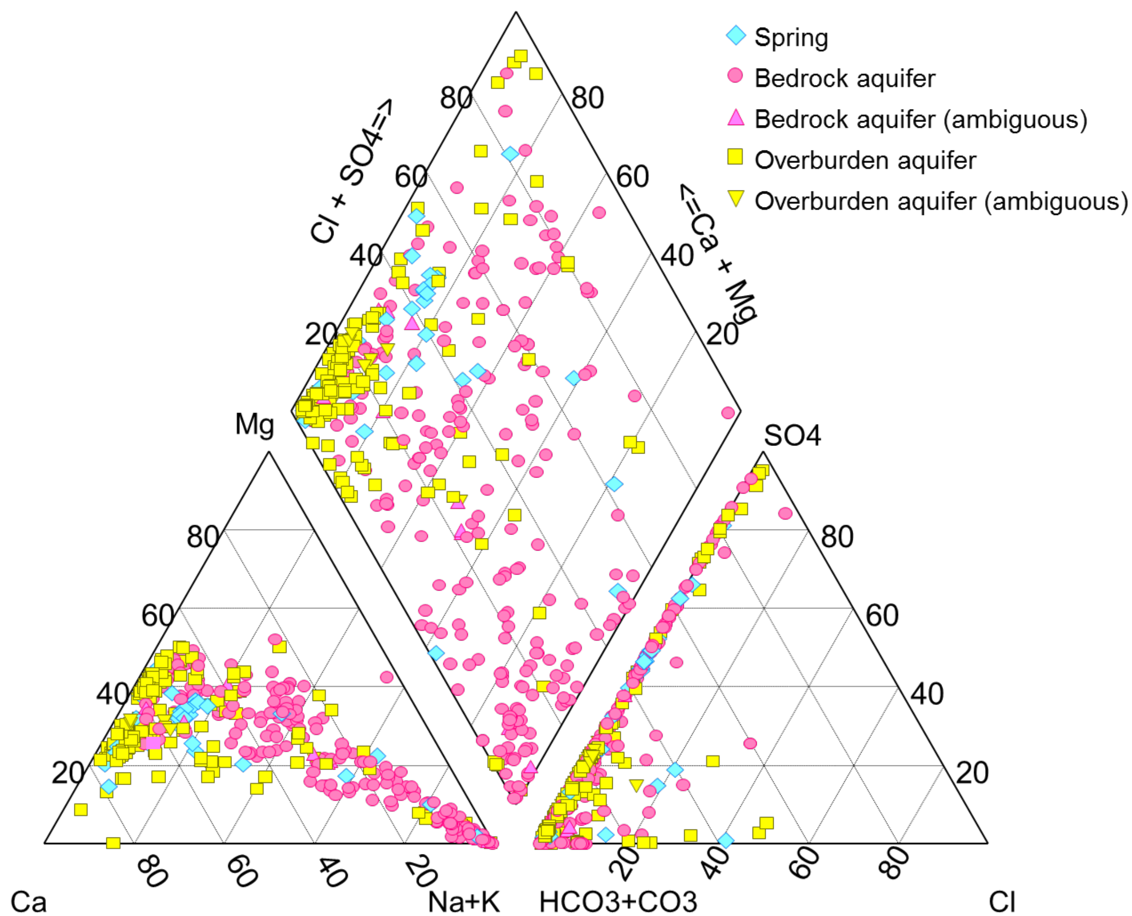


Figure 26. Piper plot for wells with major ions tested, classified by aquifer type (surficial aquifers and bedrock)

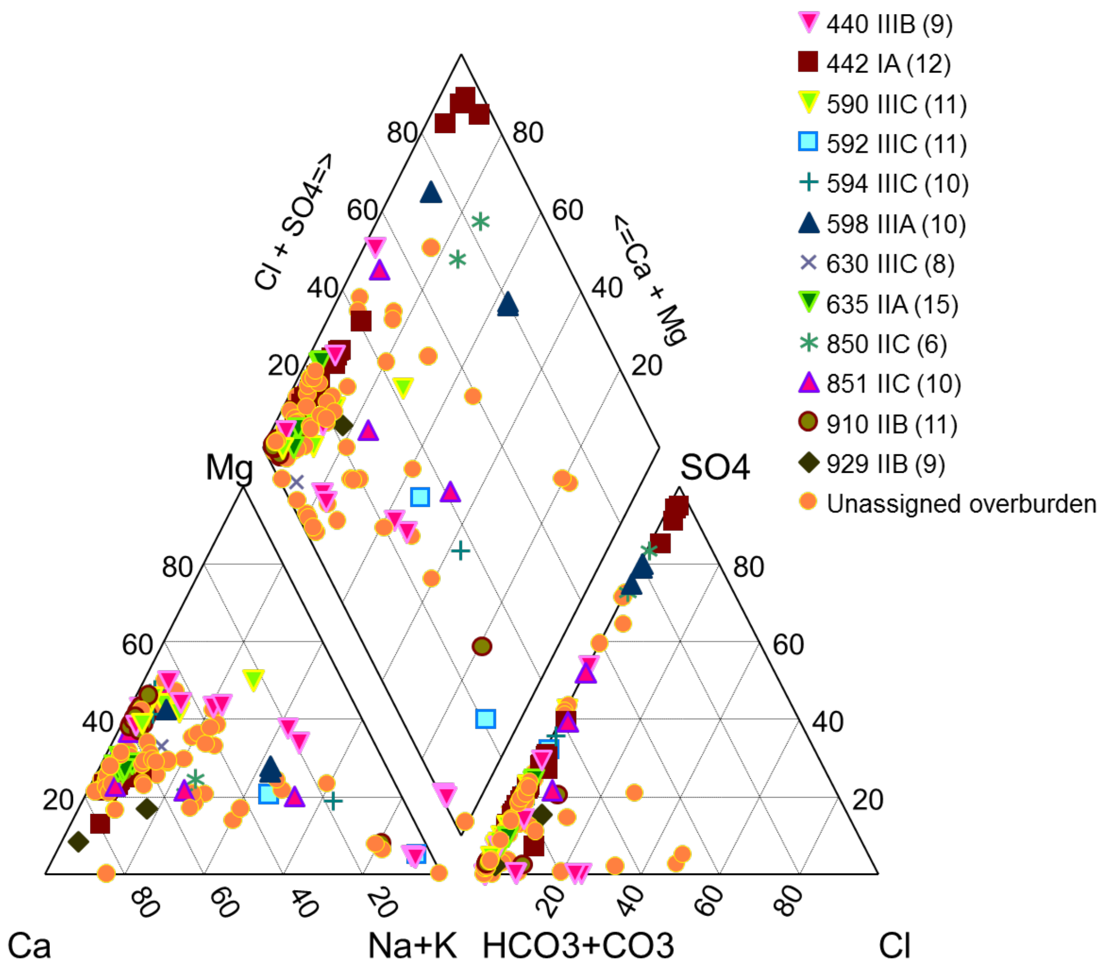


Figure 27. Piper plot for wells in surficial aquifers classified by mapped aquifer

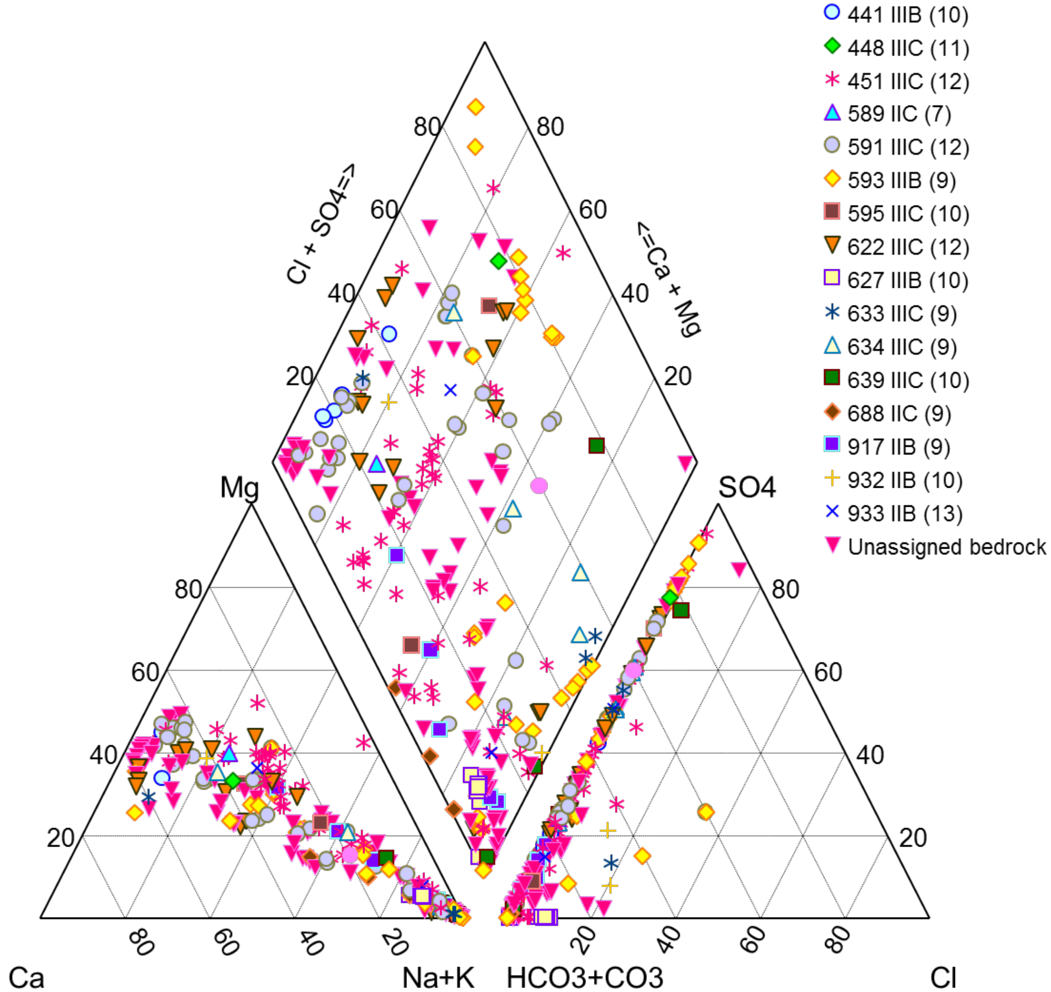


Figure 28. Piper plot for bedrock wells classified by mapped aquifer

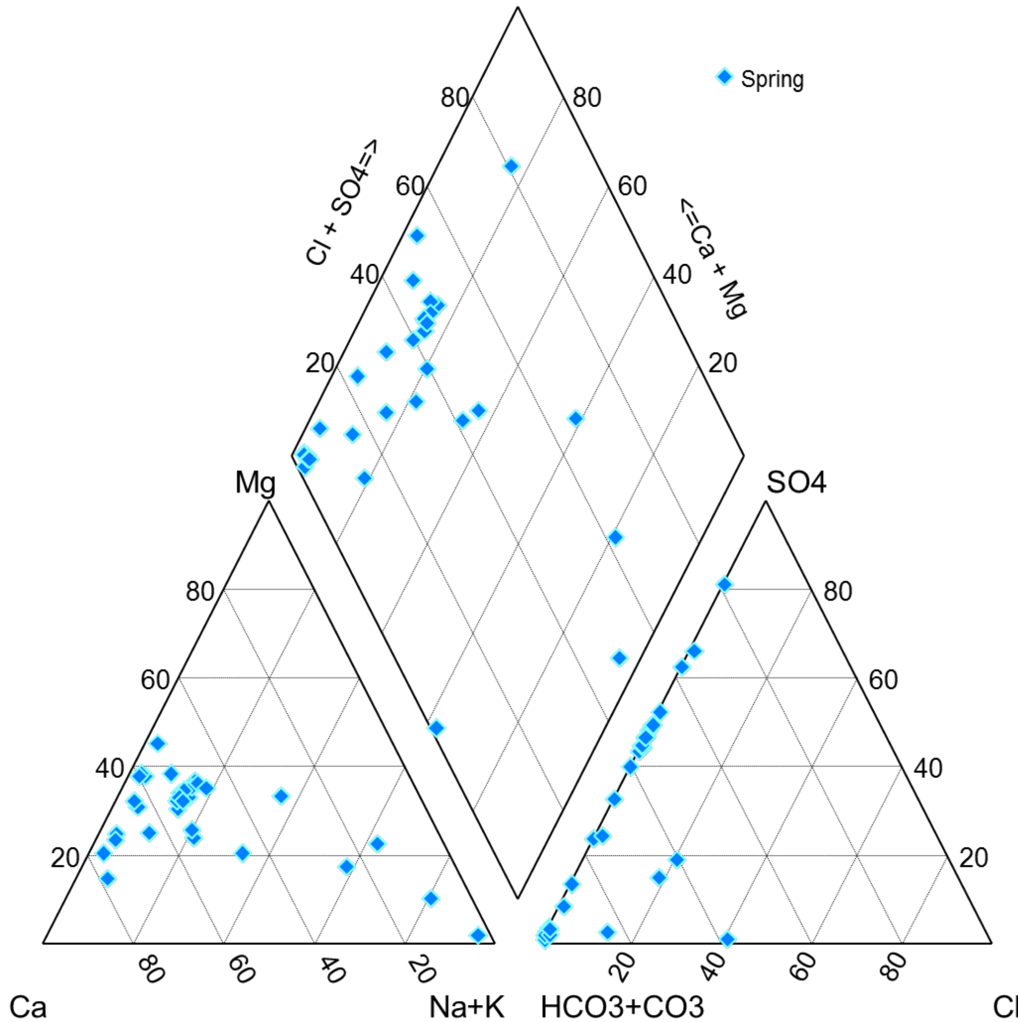


Figure 29. Piper plot for samples collected from springs

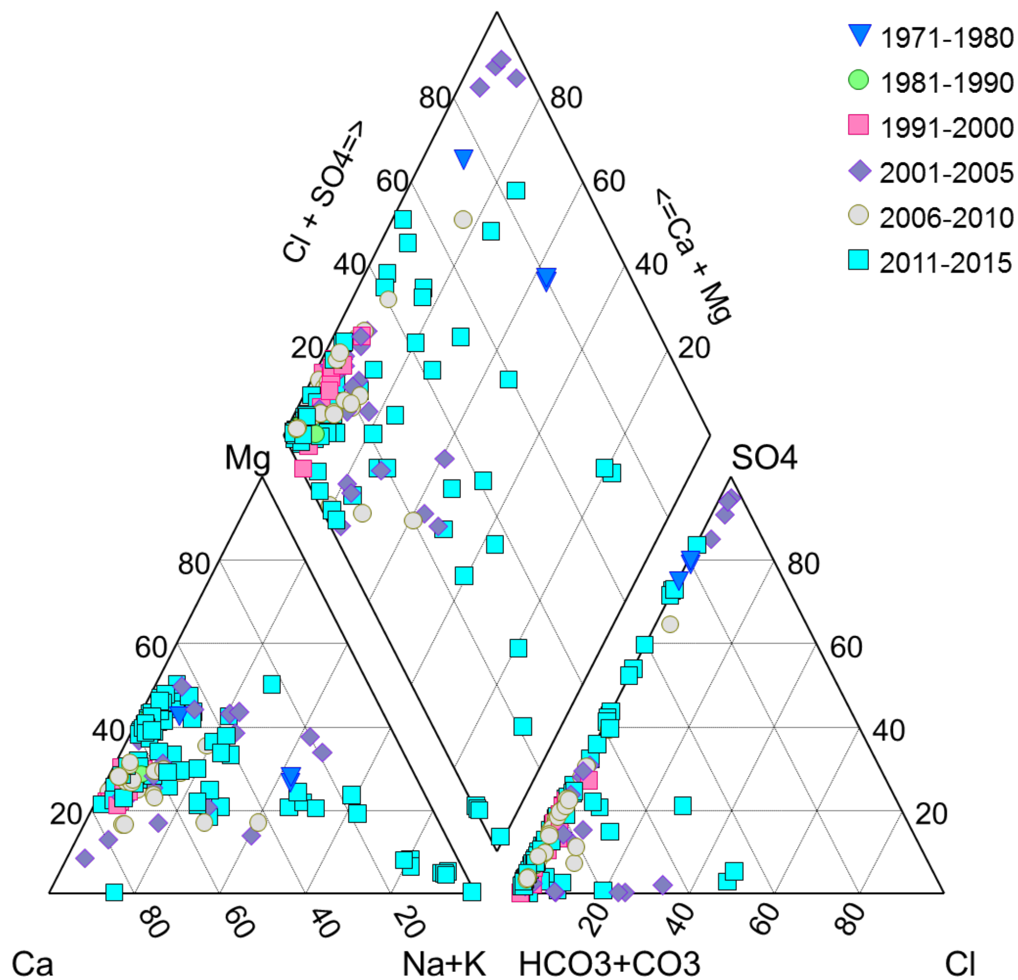


Figure 30. Piper plot for wells in surficial aquifers grouped by sampling periods

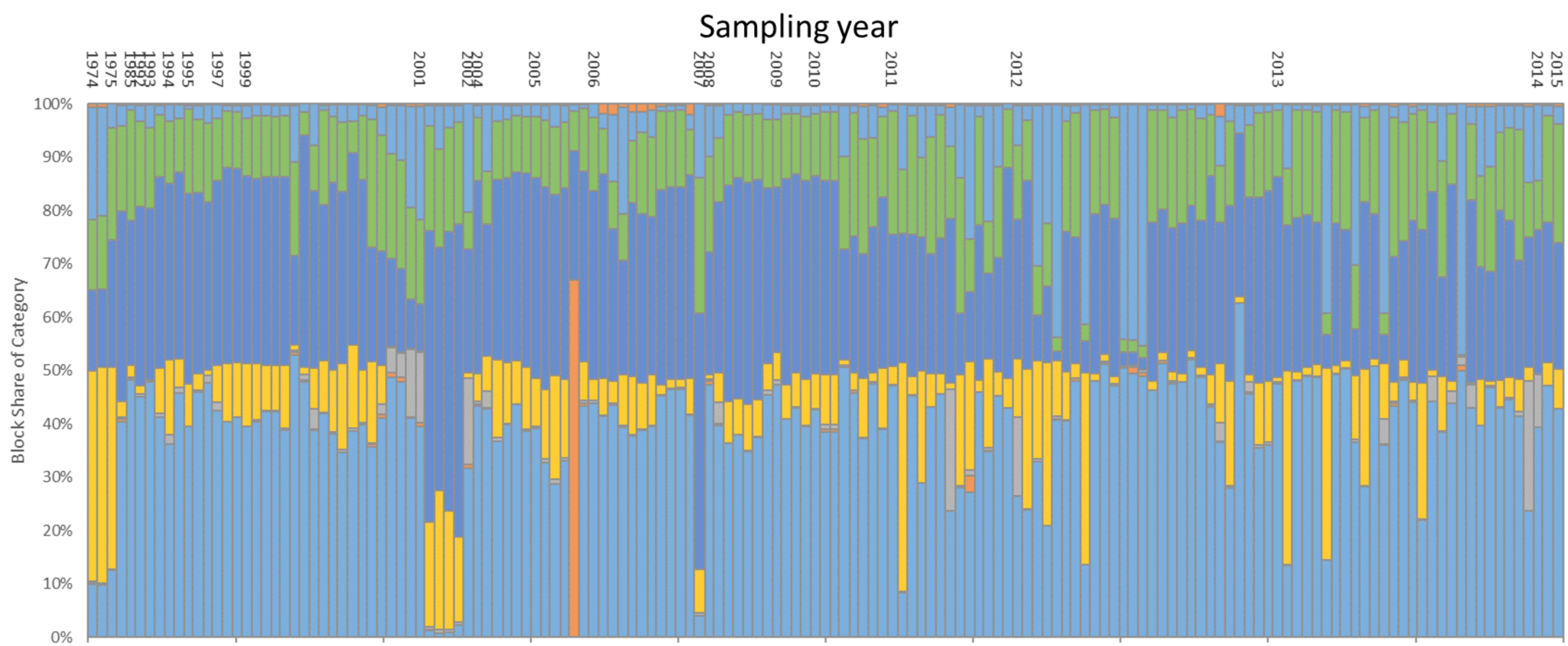


Figure 31. Marimekko chart showing the evolution of water type for wells in surficial aquifers

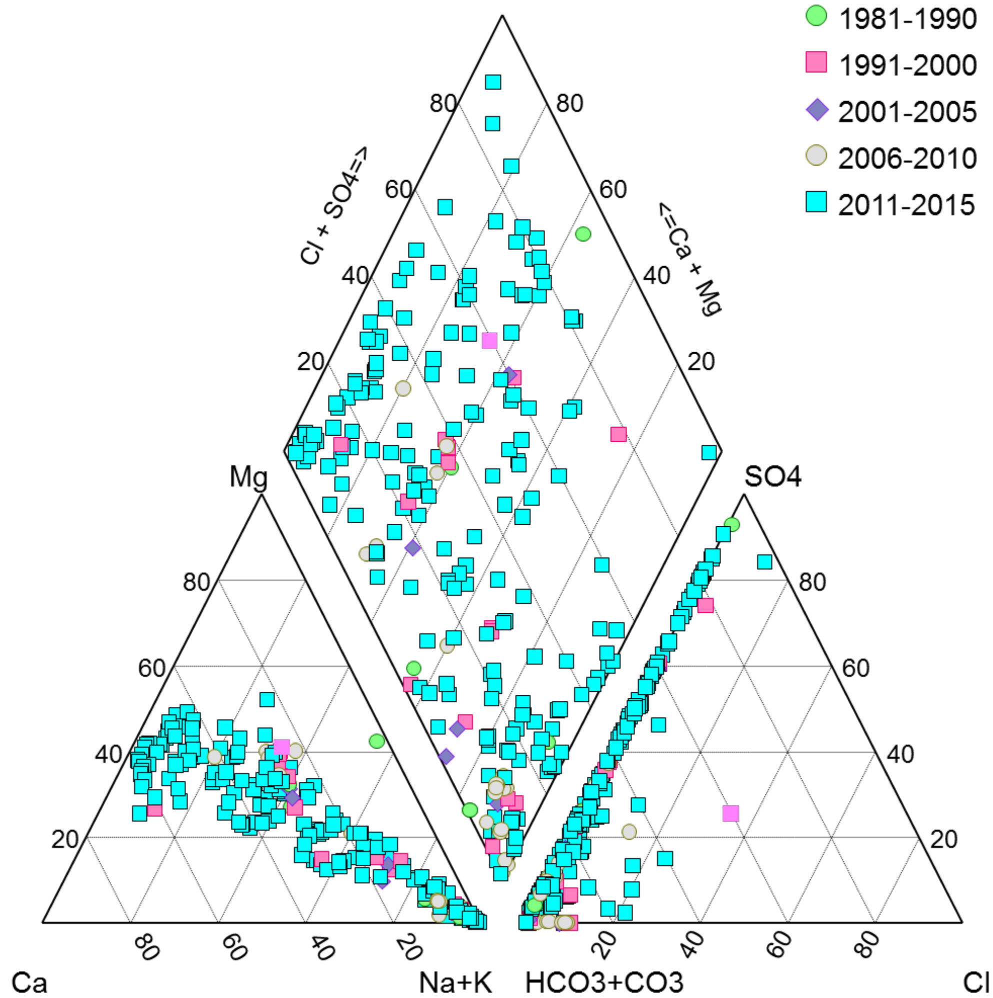


Figure 32. Piper plot for bedrock wells grouped by sampling periods

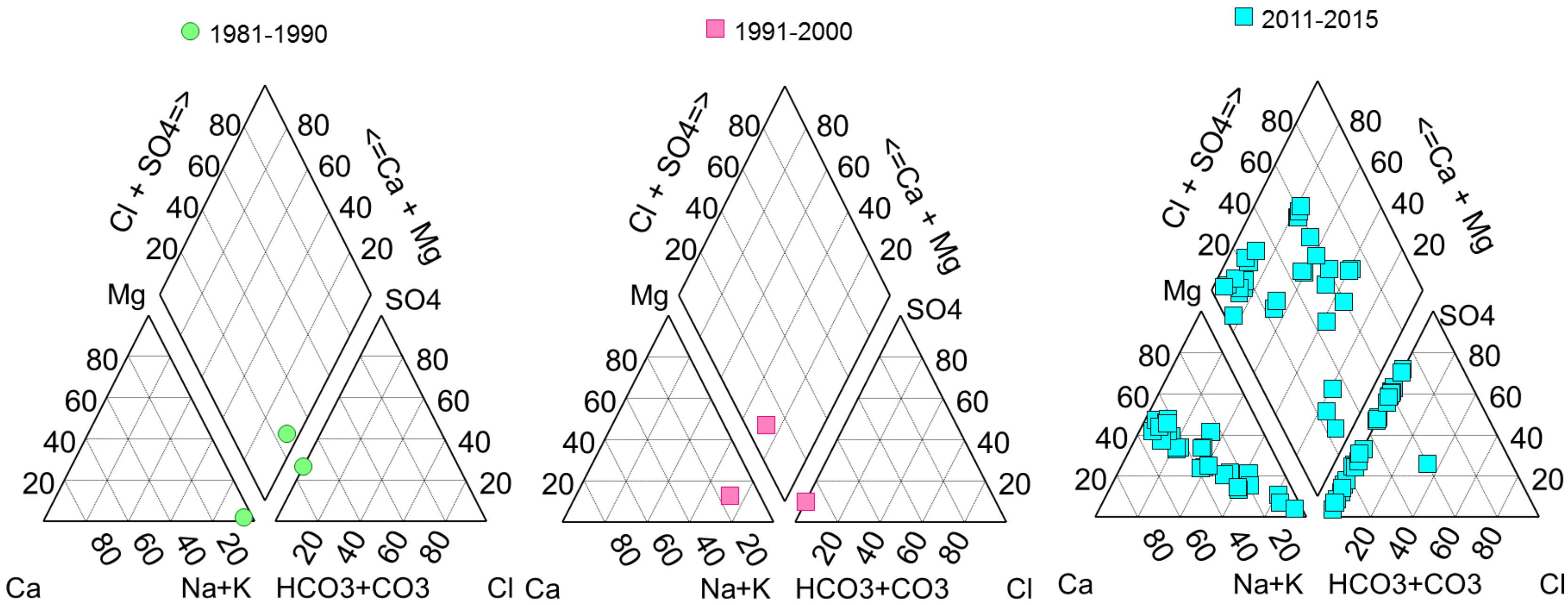


Figure 33. Example of piper plot over time for aquifer 591 IIIC (12)

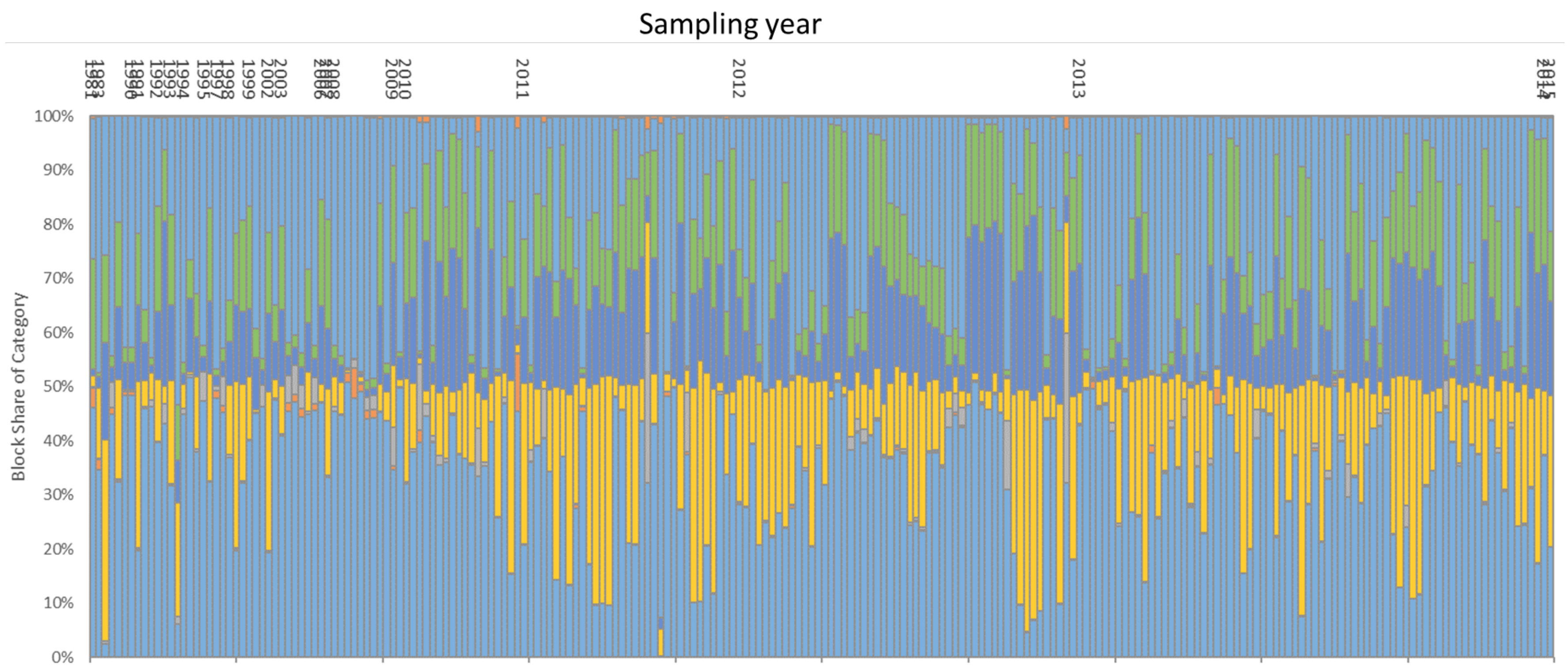


Figure 34. Marimekko chart showing the evolution of water type for bedrock wells

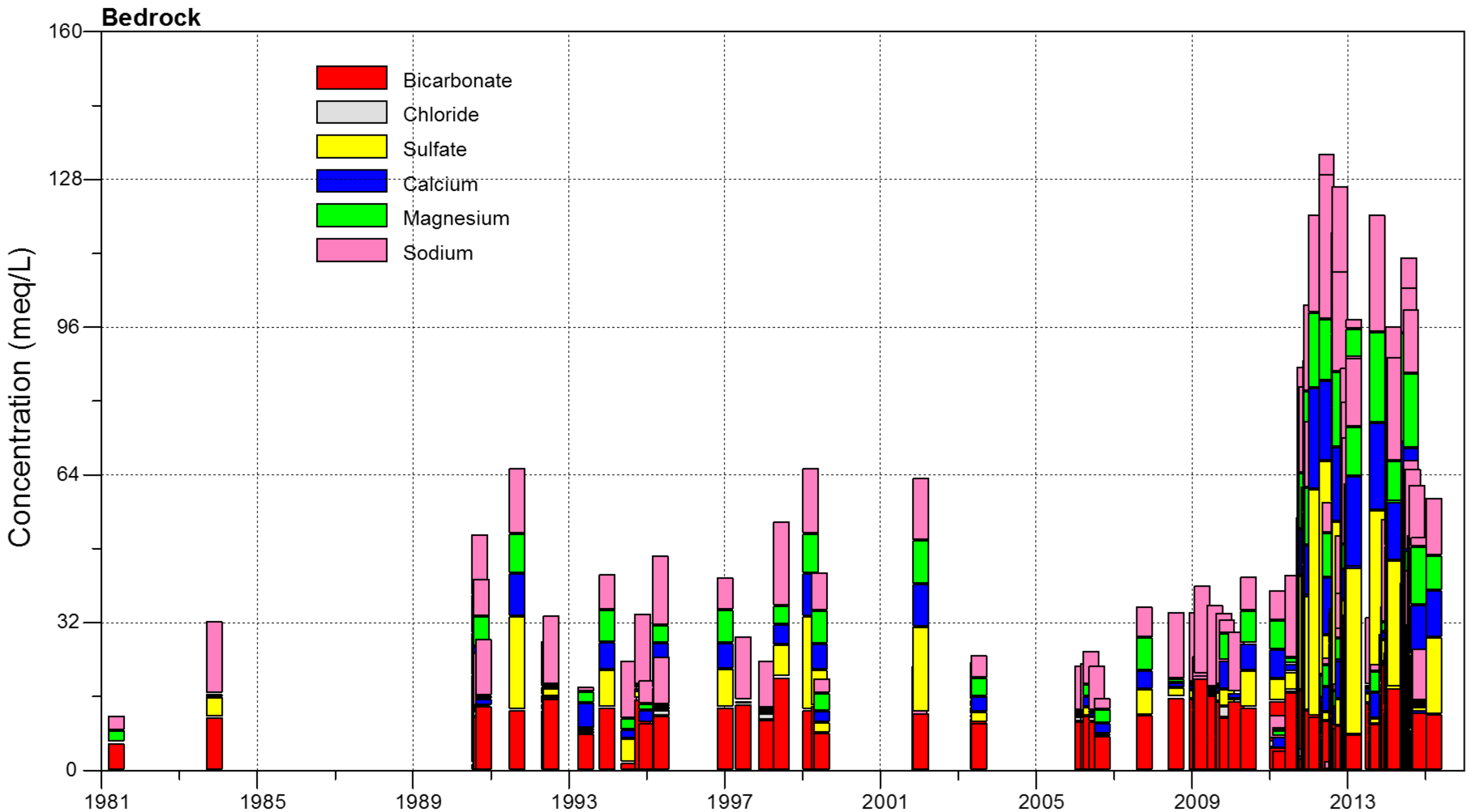


Figure 35. Bar plot over time for the major ions (Ca, Mg, Na, HCO3, Cl and SO4) for samples taken from bedrock wells

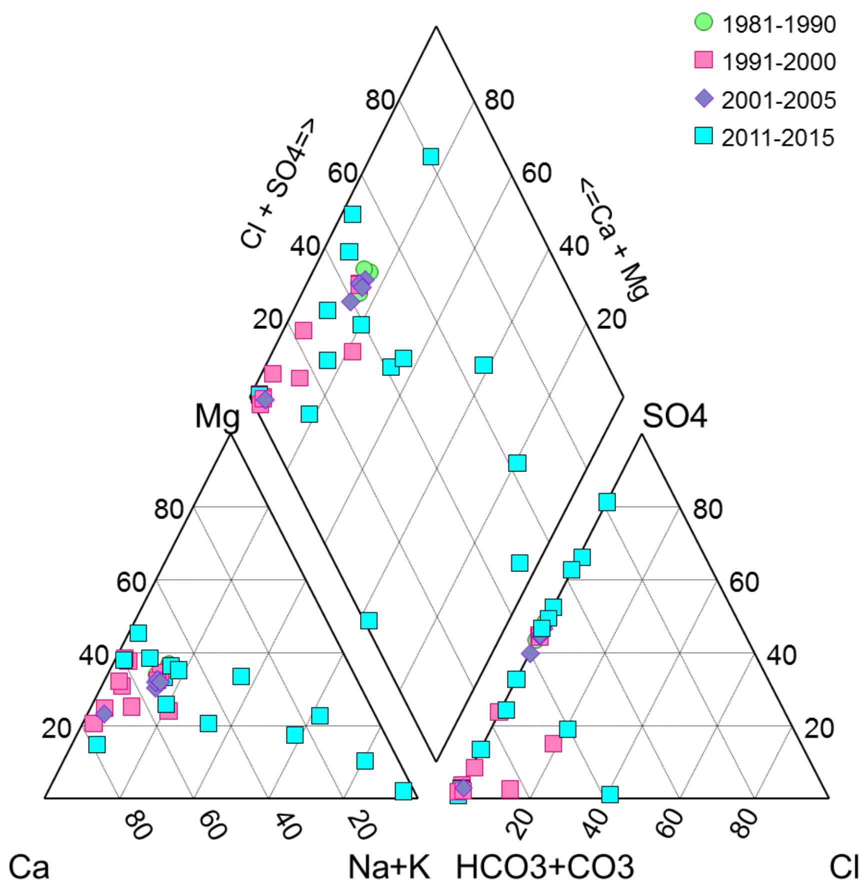


Figure 36. Piper plot for samples taken from springs grouped by sampling periods

2.2 Comparison with water quality guidelines

2.2.1 Comparison with Federal guidelines

Water quality data was compared with the federal water quality guideline for protection of aquatic life, drinking water, agriculture-livestock, agriculture-irrigation and recreation. Although the aquatic life guideline was included in this groundwater analysis for comparison (because groundwater discharges to streams and surface water), more emphasis was given to the comparison of the guidelines applying to the use of groundwater for drinking water and agriculture.

Figure 44 shows the number of samples exceeding the federal guidelines and Figure 45 displays the percentage of samples exceeding the federal guidelines. The guideline for protecting aquatic life is the most stringent followed by drinking water and agriculture. Four metals exceeded the most the aquatic life guideline allows: copper 49%, iron 40%, arsenic 34%, and zinc 26%. In addition, 48% of the samples exceed the threshold for fluoride for aquatic life.

Regarding drinking water (CDWQG), three metals presented the highest percentage of exceedance: manganese 55% (Aesthetic Objective-AO), iron 40% (AO) and arsenic 18% (Maximum acceptable concentration-MAC). In addition, two major ions and one physical parameter reported the highest percentage of exceedance: sodium 33% (AO), sulphate 15% (AO) and total dissolved solids 56% (AO)

Three metals (manganese 26%, boron 12%, and molybdenum 9%) and total dissolved solids (56%) exceed the most the agriculture guideline for irrigation purposes. However, when compared with agriculture-livestock guidelines, only sulphate presents the highest percentage of exceedance (9%). Finally, only pH (over 1%) was reported to exceed the recreational guideline.

Appendix 9 presents maps showing the location where groundwater samples exceed the federal guidelines considered in this analysis. Maps are presented as a percentage of exceedance which is the ratio between number of exceedance and total number of samples. Additionally, Appendix 9 also includes bar charts for both number and percentage of exceedance divided into four time periods: 1) samples collected prior 2001, 2) samples collected between 2001 and 2005, 3) 2006-2010 and 4) samples taken between 2011 and 2015.

2.2.2 Comparison with Provincial guidelines

Five sets of provincial guidelines (aquatic life, drinking water, agriculture-irrigation, agriculture-livestock, and wildlife) were included for the water quality exceedance analysis. The aquatic life guideline is the most stringent followed by livestock, wildlife, drinking water and irrigation.

Figure 46 and Figure 47 display the number and percentage of samples exceeding the BCMOE provincial guidelines. Four metals (iron dissolved 66%, arsenic 34%, iron total 24%, and copper 17%) and dissolved oxygen (94%) present the highest percentage of exceedance for the aquatic life guideline.

Arsenic, aluminum total, copper, lead, molybdenum, and zinc are the metals exceeding thresholds for livestock watering. Sulphate has the highest percentage of exceedance (9%).

For the protection of wildlife, six metals exceed the guideline (arsenic, aluminum total, copper, lead, molybdenum, and selenium). In addition, fluoride, nitrate and nitrite also exceed the guideline. The percentage of exceedance is below 4% for all the reported parameters.

The BCMOE provincial guideline for drinking water is less stringent than the federal drinking water guideline. Four metals (copper, lead, molybdenum and zinc) exceed the provincial drinking water guideline, but the percentage of exceedance is below 2%. However, 15% of the samples exceed this guideline for sulphate.

Eight parameters exceed the irrigation guideline. Six are metals (aluminum total, arsenic, boron, copper, molybdenum and zinc) and two are major ions (chloride, fluoride). The percentage of exceedance is below 4% except for boron, which has the highest percentage of exceedance at 12%.

Maps showing the locations where samples exceed the set of provincial guidelines are presented in Appendix 10. In addition, Appendix 10 shows the evolution of exceedance summarized in bar plots considering four time periods: 1) samples collected before 2001, 2) samples collected between 2001 and 2005, 3) 2006 and 2010 and 4) samples collected between 2011 and 2015.

2.3 Variation of water chemistry over time

2.3.1 Scatter charts

Scatter plots for all the stations and mapped aquifers were assessed using a built-in excel macro. The spreadsheet allows the choice of the aquifer, station, and parameters. In addition, the scatter plots include the BCMOE guidelines for reference. Figure 48 shows an example of a scatter plot, generated using the built-in macro, for Zinc (total) in aquifer 451 IIIC (12) located near Fort St. John. Appendix 11 presents the scatter plots for all the aquifers considered within this analysis.

2.3.2 Trend analysis

Similar to surface water trend analysis, four methods were used to estimate trends in groundwater quality: 1) Mann-Kendal, 2) Seasonal Mann-Kendal, 3) Sen's test, and 4) Linear regression. Different results were obtained using the four methodologies. However, a trend result was assigned to a parameter only if at least three of the four methods used provided the same answer. Otherwise, the trend results were qualified as ambiguous.

In addition, visual verification was completed in all the parameters for all the stations. Only stations with at least three years of data and at least three samples were considered in the analysis.

Trend results have been assigned to 47 parameters from which six correspond to physical properties (e.g., pH, TDS), five parameters to nutrients (e.g., nitrate, nitrogen), eight to major ions (e.g., calcium, sulphate) and 28 parameters to metals (e.g., aluminum, zinc). Appendix 12 presents the resulting trend maps for all the parameters considered within the analysis.

As an example of the completed trend analyses, Figure 49 shows some results for barium. There are six stations (5, 293, 296, 246, 247, and 239) which display increasing trends for barium and three stations (4, 237 and 299) indicating a decreasing trend. Their location is shown in Figure 49. Station 296 presents the highest concentration of barium (1.06 mg/L) in September 30, 2009. Figure 50 to Figure 55 show the scatter plots for barium for the stations with an increasing trend.

Barium is an important element because it is typically present at very low concentrations in natural shallow groundwater and its concentration is not expected to change. On the other hand, barium (as barium sulfate) is used as a heavy additive in oil well drilling fluid and is also present at high concentrations in the deep saline groundwater in the Montney shale gas region. Therefore, the observed increase in barium in groundwater could possibly be a result of the intense drilling activity in the region, through mobilization of deep groundwater containing higher concentration of barium, or the release of barium into the shallow aquifers during drilling activities.

Station 5 which is part of the provincial observation well network (monitoring well No 286 Tumbler Ridge), in addition to showing an increasing trend of barium, also shows increasing trends for alkalinity, calcium (dissolved), chloride, magnesium (dissolved), potassium (dissolved), sodium (dissolved), sulfate, and TDS. Figure 56 shows concentrations versus time for chloride, sodium, potassium and sulfate for Station 5. The observed changes in water quality warrants a more detailed assessment of the causes of such changes.

F. Interconnection Between Surface Water and Groundwater

1 Basic Principles

Groundwater interacts closely with surface water. Groundwater can discharge into a stream or lake, or can receive water from the stream or lake (Figure 37) depending on relative water levels. Depending on hydrologic conditions, an aquifer can discharge water into a surface water body at certain times and receive water from surface water body at other times.

An aquifer that supplies a stream provides the stream's base flow. Indeed, the sources of water to streams are (Figure 38): precipitation that falls directly onto a stream, which is a relatively small component of total streamflow;

- surface runoff that travels over the land surface to a stream channel; and
- groundwater discharge, which is commonly referred to as base flow.

Surface runoff is important during and following storm events, and is referred to as the direct-runoff component of stream flow. Another source of runoff is snow melt, mostly in spring and early summer, a function of the snow accumulation and land topography.

Groundwater, on the other hand, is most important for sustaining the flow of a stream during periods between storms and during dry times of the year (USGS Circular 1376).

Groundwater plays an important role in maintaining the hydrologic balance of surface streams and other surface water body (springs, lakes, marshes, wetlands), and their associated ecosystems. Therefore, surface water and groundwater should be managed as a single hydrologic system and both the fluctuations of stream levels and discharge, and water tables in aquifers should be monitored in a coordinated way.

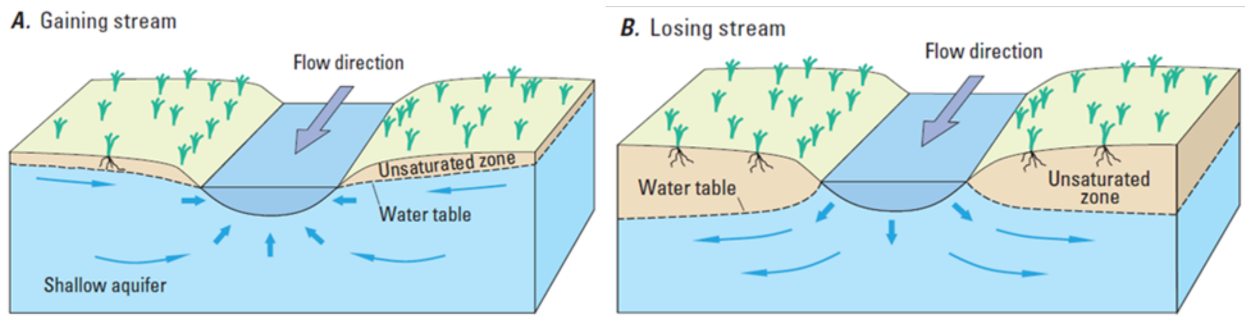


Figure 37. Gaining stream receives water from the groundwater system, B) losing stream discharges water to the groundwater system (from USGS Circular 1376)

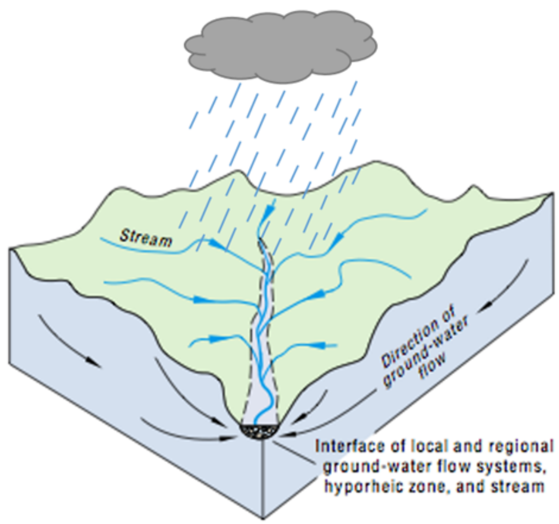


Figure 38. Streams hydrological components (modified from USGS Circular 1139)

2 Groundwater – Regulating surface water quality and temperature

In addition to providing stream base flow, groundwater plays a key role in providing a flux of water with a relatively constant geochemistry. Because of their different flow paths and residence time where they interact with soils and rocks, groundwater and surface water have different physico-chemical characteristics that affect their ecological roles (Canada's Groundwater Resources, 2014). Indeed, groundwater usually displays higher solute content, and lower dissolved oxygen than surface water. On the other hand, streams present a higher variability in the concentration of their constituting elements. Therefore, the role played by groundwater in balancing the physico-chemical characteristics of surface water is very important for species and ecosystems that rely on a chemically stable environment for their survival.

Groundwater also plays a key role in regulating water temperature. The thermal insulation provided by the ground, combined with the slow movement of groundwater, results in groundwater being at a temperature equivalent to the annual air temperature. Therefore, groundwater will cool surface water during the warmer months and provide warmer water during the colder months. This is critical for small streams where the winter base flow provided by groundwater prevents them from freezing completely. Similarly, the cooling effect during the warmer months (which also correspond to periods of low flows) prevents surface water from reaching temperatures that could be lethal to fish.

G. Human (anthropogenic) Activities and Impacts on Water

1 Anthropogenic (Human) activities and potential impacts

This section is included in this report to briefly show how human activities can affect surface water and groundwater quality, and the types of human activities typically carried out in the PRRD. Assessing the source of contamination and the effects contamination could have on water quality was beyond the scope of the study. However, we are introducing this information for non-technical readers with the intent to show how activities carried out at the surface and in the subsurface could potentially affect water quality, and the potential link between water and fluids to depths up to several kilometers. This is provided as a context to understand some of the conclusions and recommendations of this report.

Anthropogenic activities at the surface and subsurface can affect groundwater flow dynamic and groundwater quality; therefore, have consequences on stream flows and surface water quality. Some of the anthropogenic activities that may affect water quality are illustrated in Figure 39.

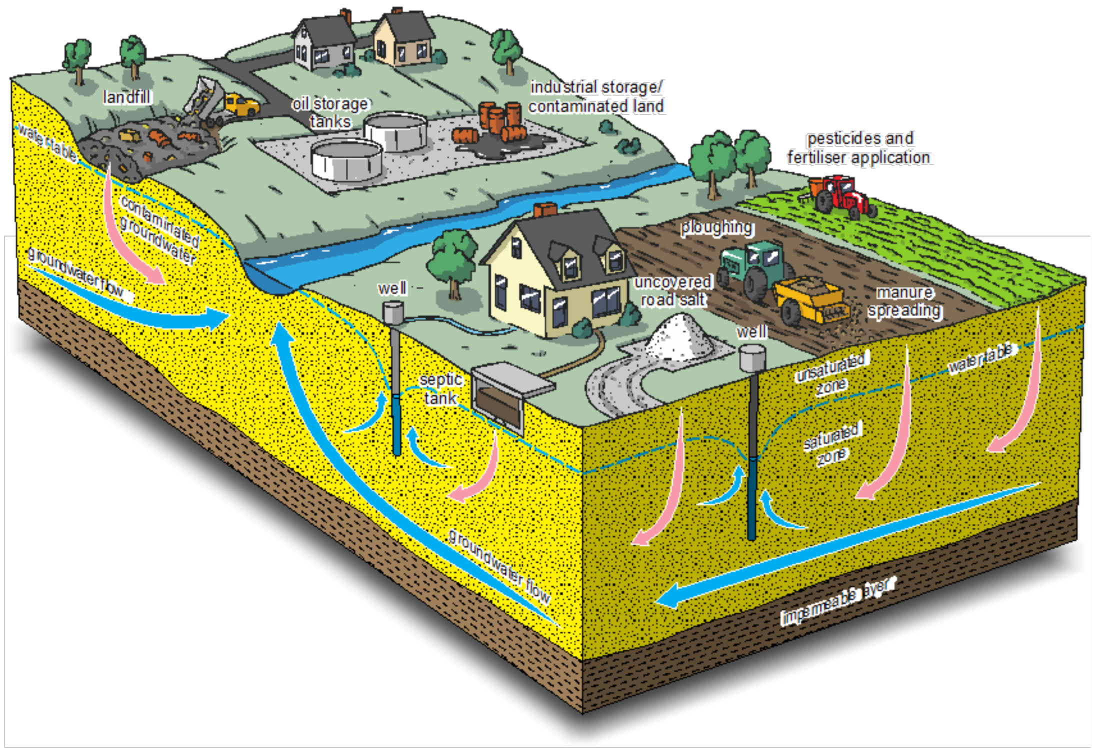


Figure 39. Human activities that may impact groundwater quality (Rivera, A., 2014)

In addition, oil and gas related activities are occurring in the PRRD. Figure 40 shows the locations of the oil and gas wells recorded in the OGC database as of August 2014. The oil and gas wells are typically completed at a depth ranging between 1.5 km and 3 km.

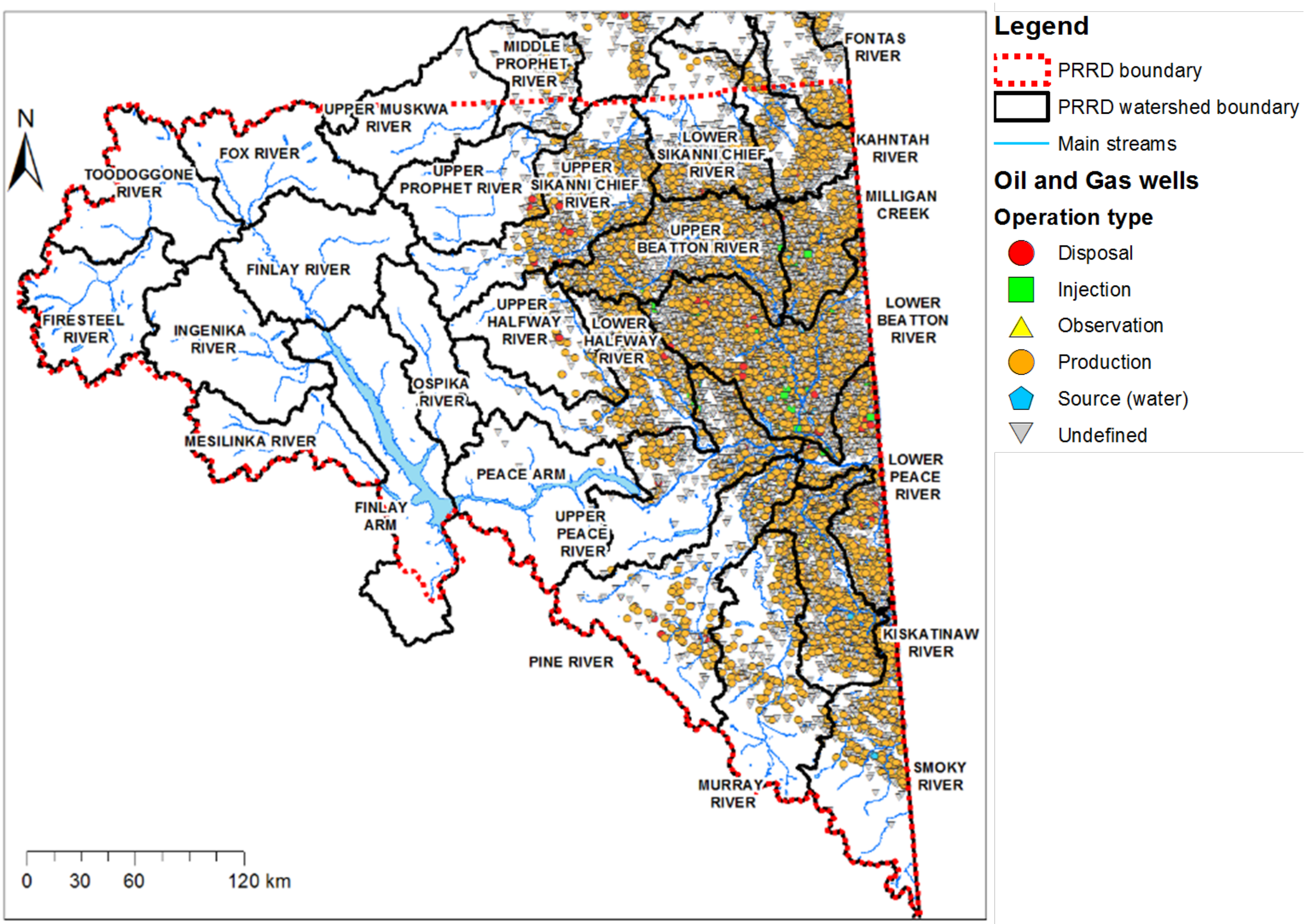


Figure 40. Oil and gas wells across PRRD organized by operation type (approximately 24,000 wells)

There are several risks of modification of the water quality related to this industry, in particular for shale gas wells, as illustrated by Vengosh and al. (2014) (Figure 41).

Vengosh identifies the reasons for a potential modification of the water quality to result from:

(1) overuse of water that could lead to depletion and water- quality degradation particularly in water-scarce areas;
(2) surface water and shallow groundwater contamination from spills and leaks of wastewater storage and open pits near drilling;
(3) disposal of inadequately treated wastewater to local streams and accumulation of contaminant residues in disposal sites;
(4) leaks of storage ponds that are used for deep-well injection;
(5) shallow aquifer contamination by stray gas that originated from the target shale gas formation through leaking well casing. The stray gas contamination can potentially be followed by salt and chemical contamination from hydraulic fracturing fluids and/or formational waters;
(6) shallow aquifer contamination by stray gas through leaking of conventional oil and gas wells casing;
(7) shallow aquifer contamination by stray gas that originated from intermediate geological formations through annulus leaking of either shale gas or conventional oil and gas wells;
(8) shallow aquifer contamination through abandoned oil and gas wells;
(9) flow of gas and saline water directly from deep formation waters to shallow aquifers; and
(10) shallow aquifer contamination through leaking of injection wells.

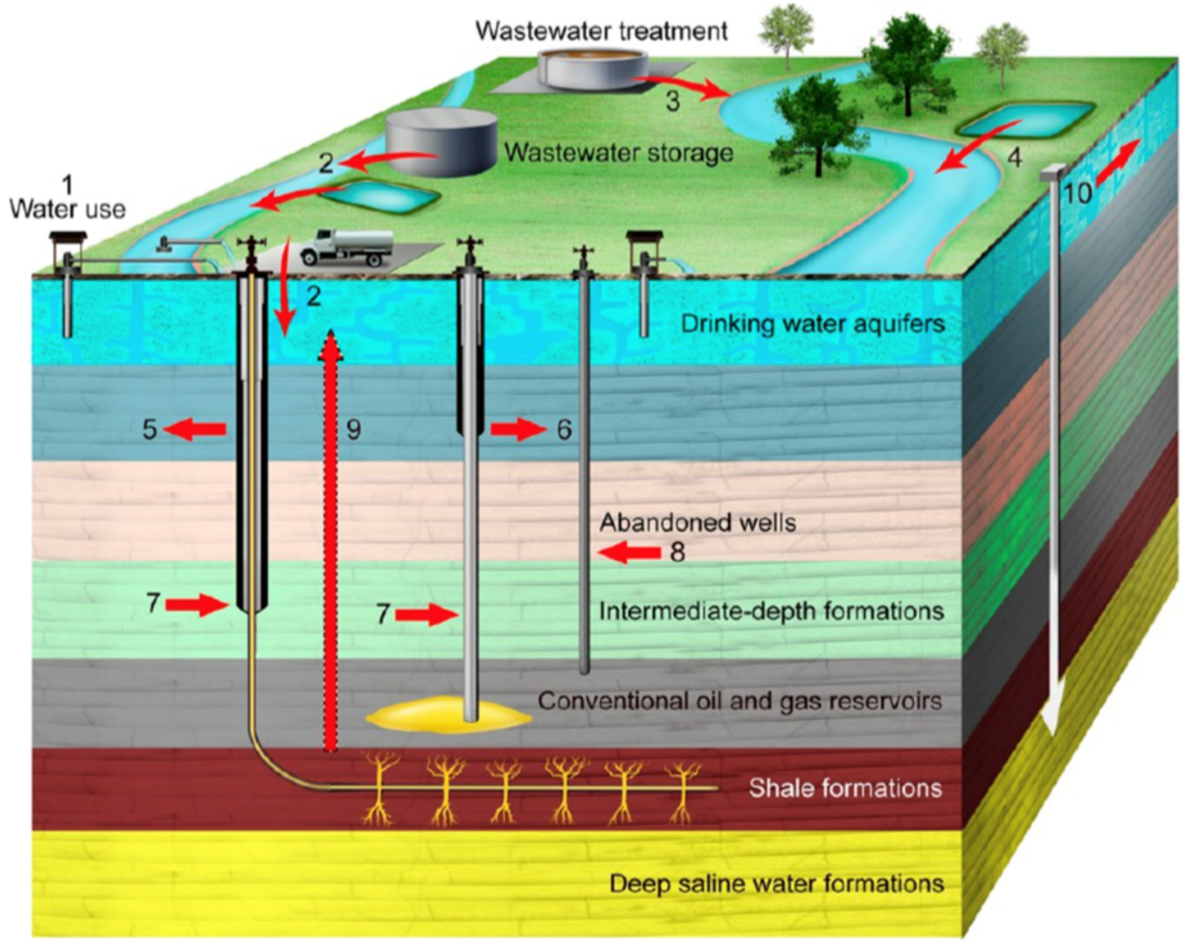


Figure 41. Schematic illustration (not to scale) of possible modes of water impacts associated with shale gas development (Vengosh et al., 2014)

2 Monitoring of the intermediate zone

The intermediate zone is located between the shallow zone where drinking water wells are typically completed and the deep zone where the oil and gas wells are completed. Figure 42 is an image conceptually describing the depth of the intermediate zone.

Unfortunately, as reported by John Cherry (2014), the intermediate zone is very poorly characterized and monitored. This is a zone where fluids of various nature are present (liquids and gases) under various pressures.

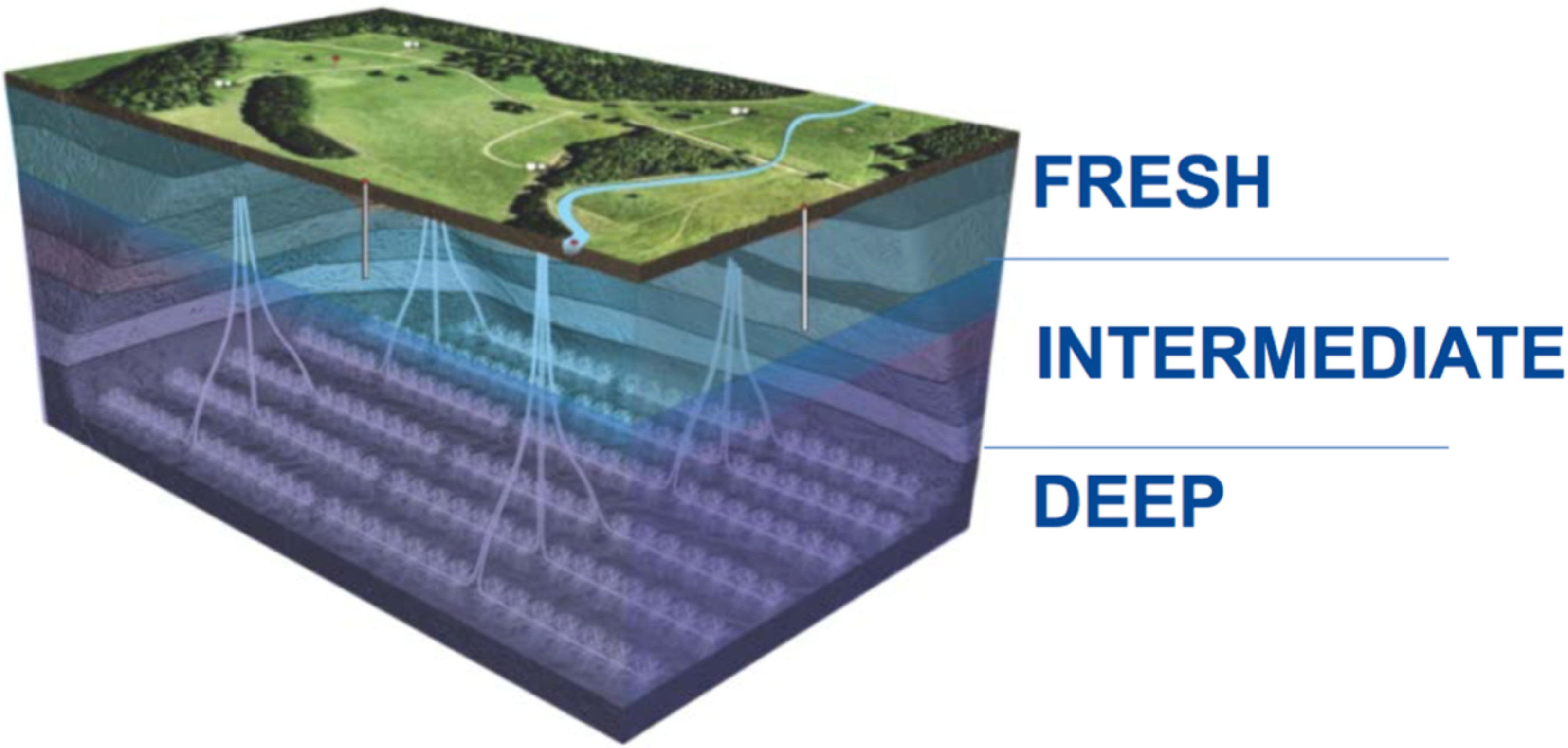


Figure 42: Three groundwater zones (modified from John Cherry, 2014)

2.1 Water quality in intermediate zone and deep aquifers

Figure 43, produced by the BC OGC, illustrates that the water quality drops with depth. The water is potable in the upper zone, where it is typically younger and has had less time to interact with the bedrock. With increasing depth, the salinity of groundwater increases, as well as the concentrations of other elements (e.g., heavy metals, etc.). Water typically encountered through most of the length drilled to reach the target plays is saline and not potable. Water extracted from the subsurface immediately following fracking and also during the operation of the shale gas wells (referred to as “flowback” or return water) will also be of poor quality.

Therefore, it is essential that data be collected from the intermediate zone because the potential migration of fluids from that zone may affect the quality of the groundwater of the shallow zone, should this happen over short periods of time (weeks or months) or longer periods of time (years or decades).

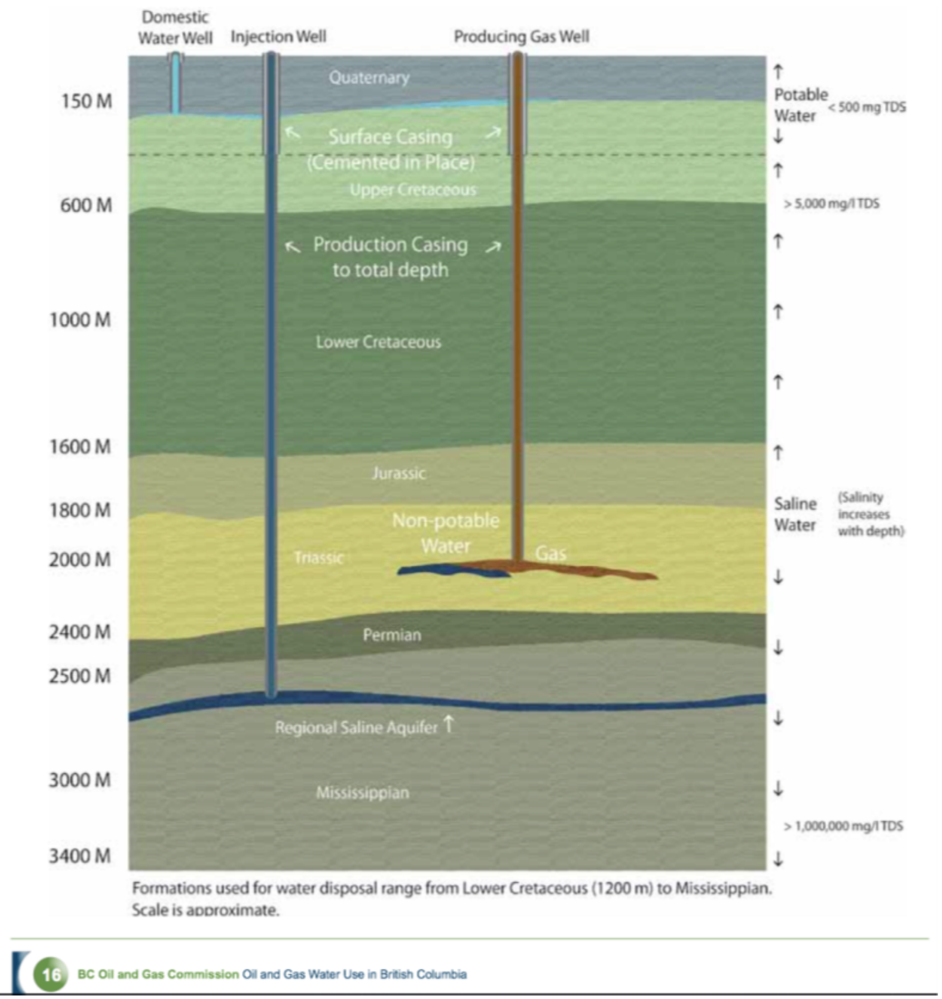


Figure 43: Salinity versus depth in deep groundwater (from BC Oil and Gas Commission)

3 Change in quality and reasons for monitoring

The completed work has revealed the following:

1. Many watersheds are and have been poorly monitored, both for surface water and groundwater;
2. The first available samples date back to 1943 and 1955 for groundwater and surface water, respectively. However, the lack of sufficient information on water, both on quality and quantity prior to the 1970s has prevented the definition of the baseline before human activities started having a footprint both at the surface and in the subsurface.
3. There is a lack in continuity defining the water quality versus time in the data set. It is very important to monitor water quality at the same location, whether it is surface water or groundwater, over several years in order to collect reliable information to define any changes or trends in water quality. Some changes may take several years or decades to be quantifiable. That would particularly be the case for groundwater of poor quality (e.g., present at depth greater than 1 km) that would travel long distances to mix with shallower groundwater and modify its water quality. For the data to be truly comparable, it should come from the same sampling location and sampling port.
4. There is a lack in spatial distribution of data defining both the surface water and the groundwater quality. For data to be interpretable, sampling and monitoring locations need to be distributed over watersheds to qualify the water quality at the various locations across the watershed (e.g., from the headwaters to the lower section of the watershed). With a proper spatial distribution, it is possible to estimate the variation in water quality as water travels through the watershed and whether the change in natural conditions and/or the activities conducted within the watershed can explain the observed changes.
5. The various media where water flows need to be monitored and analyzed so that the various pathways followed by water can be characterized. This should include the following:
    a. springs;
    b. streams;
    c. lakes;
    d. wetlands;
    e. unconfined overburden aquifers;
    f. confined overburden aquifers;
    g. bedrock aquifers; and
    h. the intermediate zone.

6. At the scale of a region, such monitoring will require concerted efforts over many years, both for planning and implementation.
7. It will require the collaboration of the many jurisdictions having control of the land and the subsurface. We understand that water quality data is available for groundwater samples collected at depth up to 2 km from the oil and gas industry (D. Kirste, peer review comment). Such information would be very valuable for the regional characterization and monitoring.

In addition, it will be costly due to the cost of analyses, the cost of installation of the network of monitoring wells to monitor groundwater, and the labor needed to collect the samples, and manage the information. Therefore, a long-term funding process must be elaborated for the successful implementation of an adequate monitoring program.

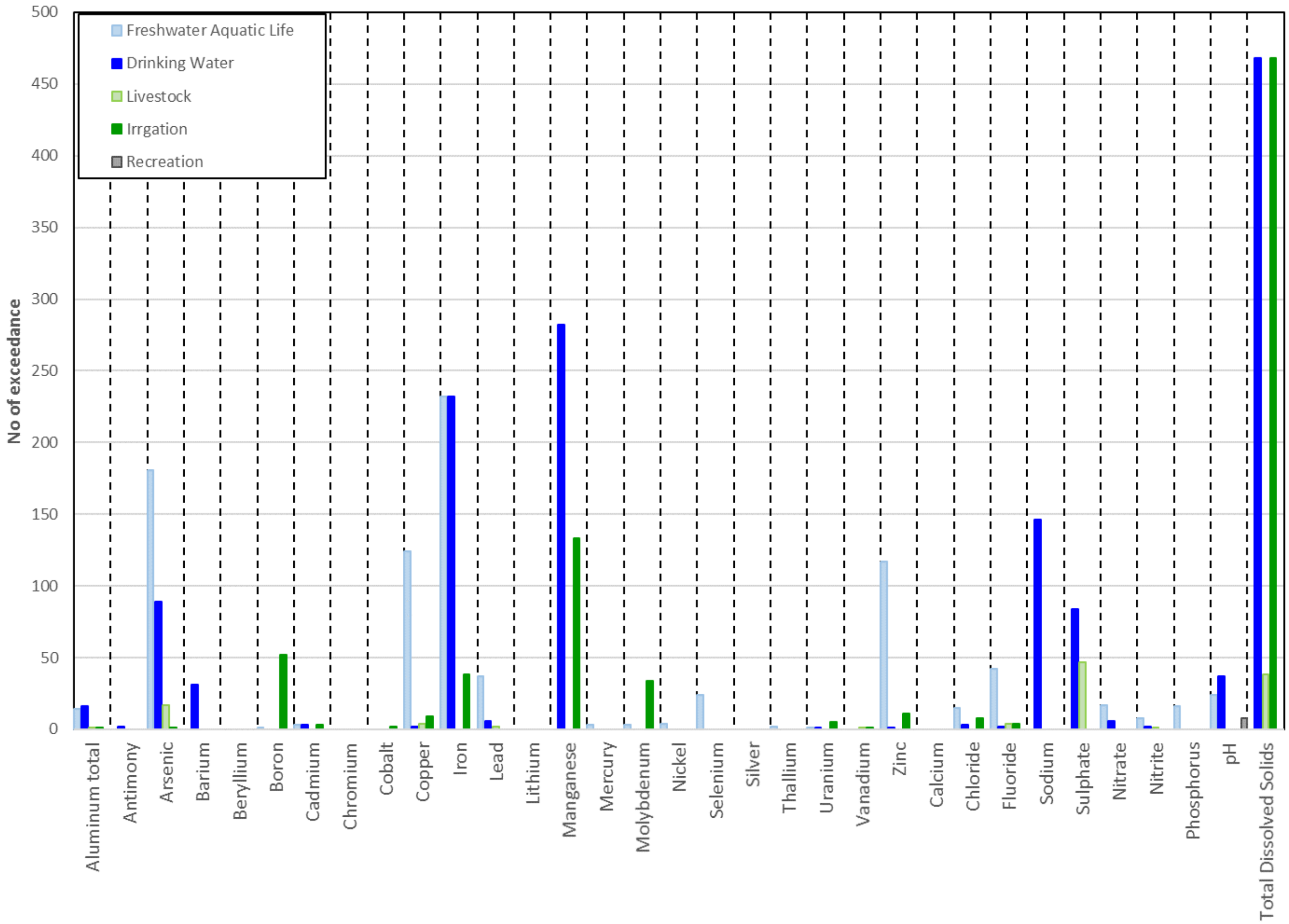


Figure 44. Number of groundwater samples exceeding federal guidelines (aquatic life, drinking water, agriculture-irrigation, agriculture-livestock, and recreation)

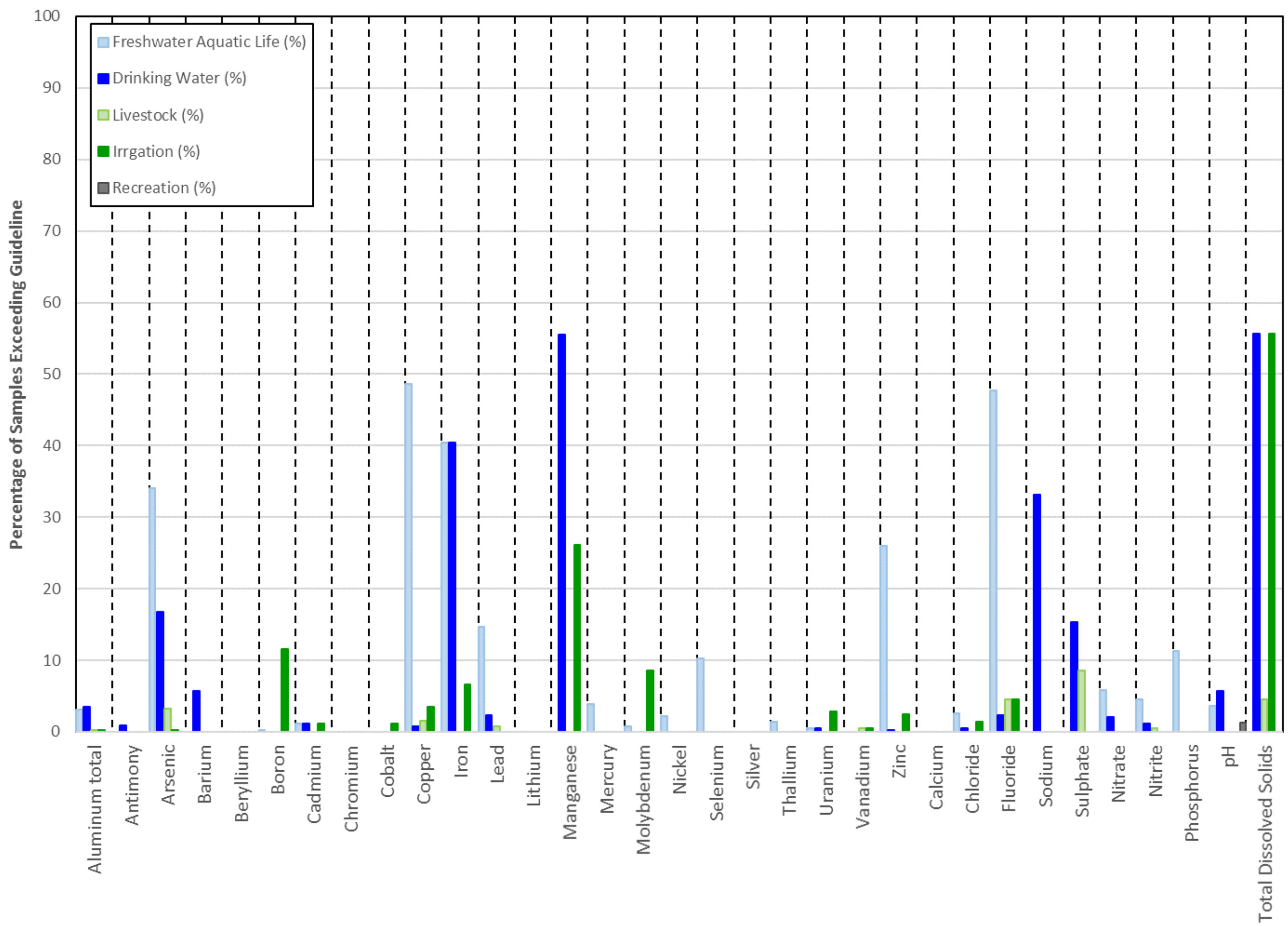


Figure 45. Percentage of groundwater samples exceeding federal guidelines (aquatic life, drinking water, agriculture-irrigation, agriculture-livestock, and recreation)

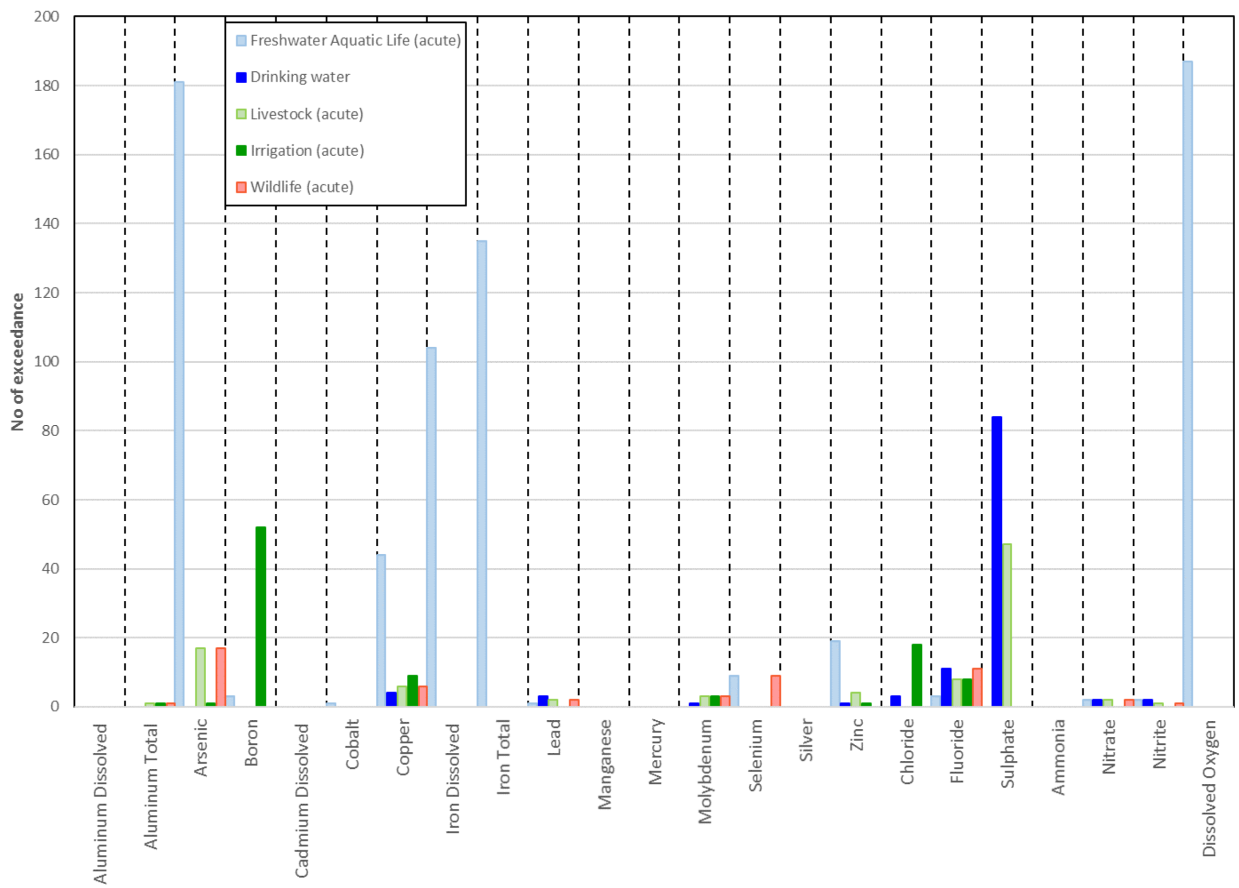


Figure 46. Number of groundwater samples exceeding BCMOE provincial guidelines (aquatic life, drinking water, agriculture-irrigation, agriculture-livestock, and wildlife)

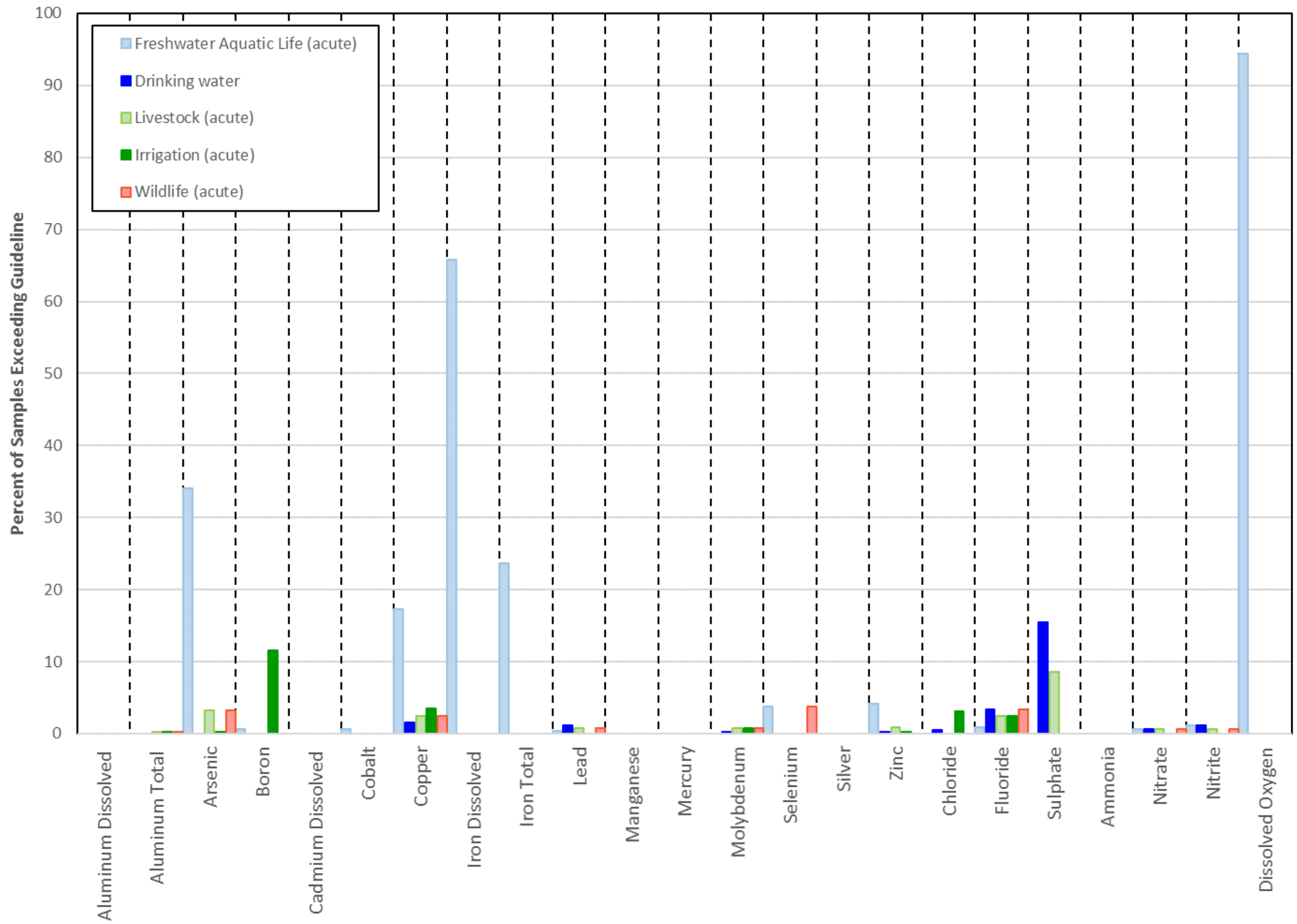


Figure 47. Percentage of groundwater samples exceeding BCMOE provincial guidelines (drinking water, agriculture-irrigation, agriculture-livestock, and wildlife)

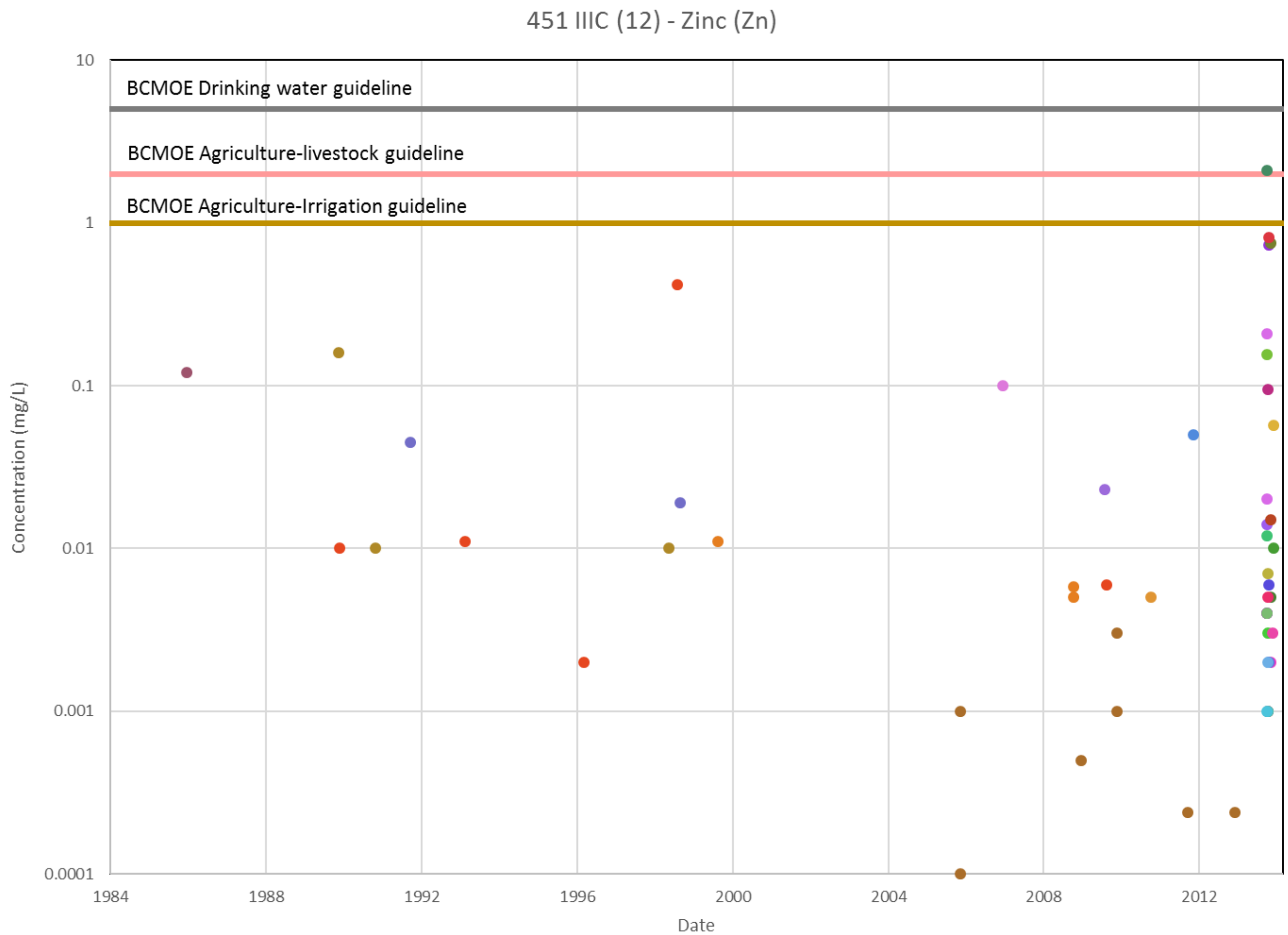


Figure 48. Zinc scatter plot for aquifer 451 IIIC (12) showing the BCMOE guidelines

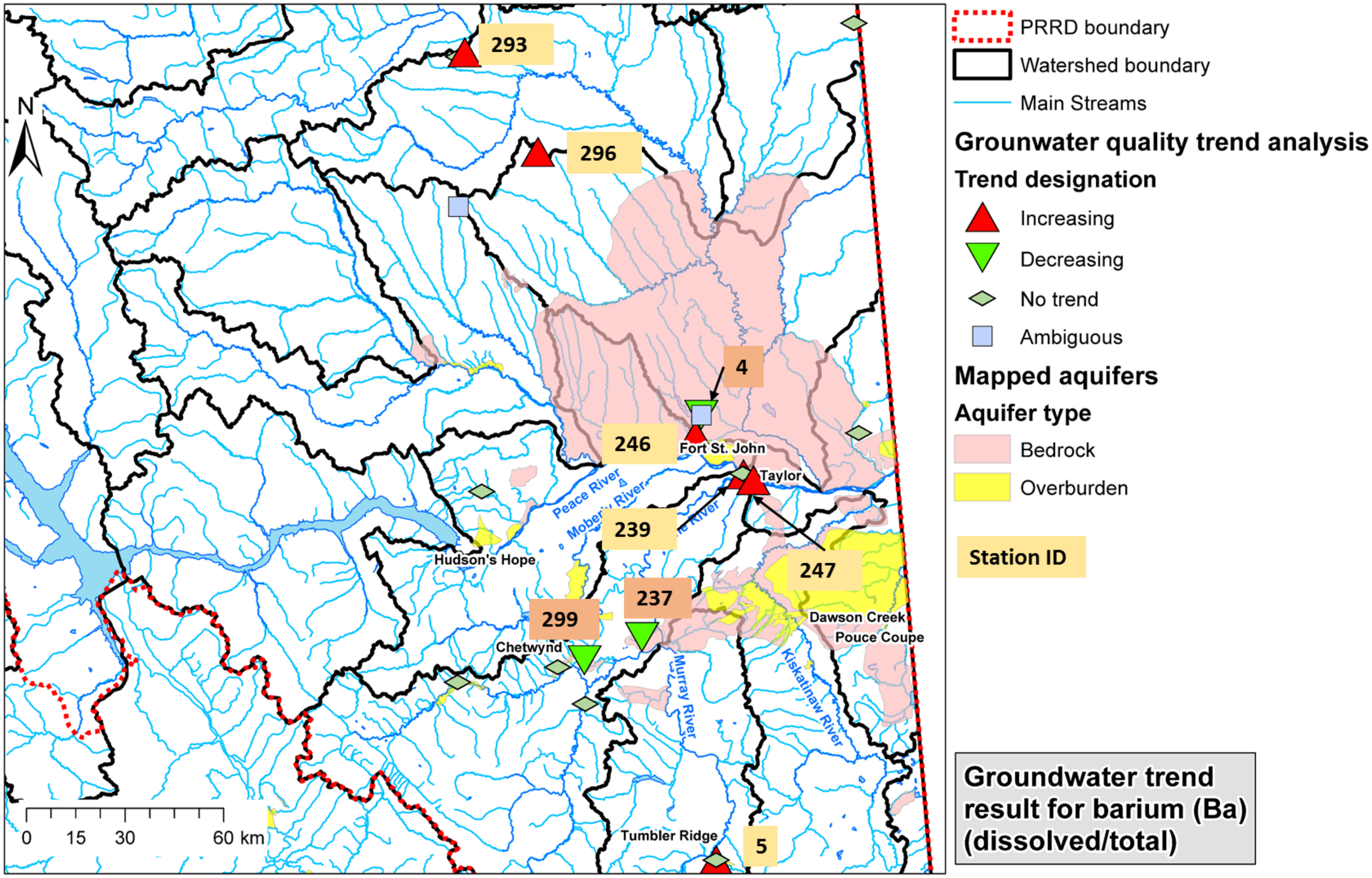


Figure 49. Barium trend results for groundwater stations with over three years of data and more than three samples

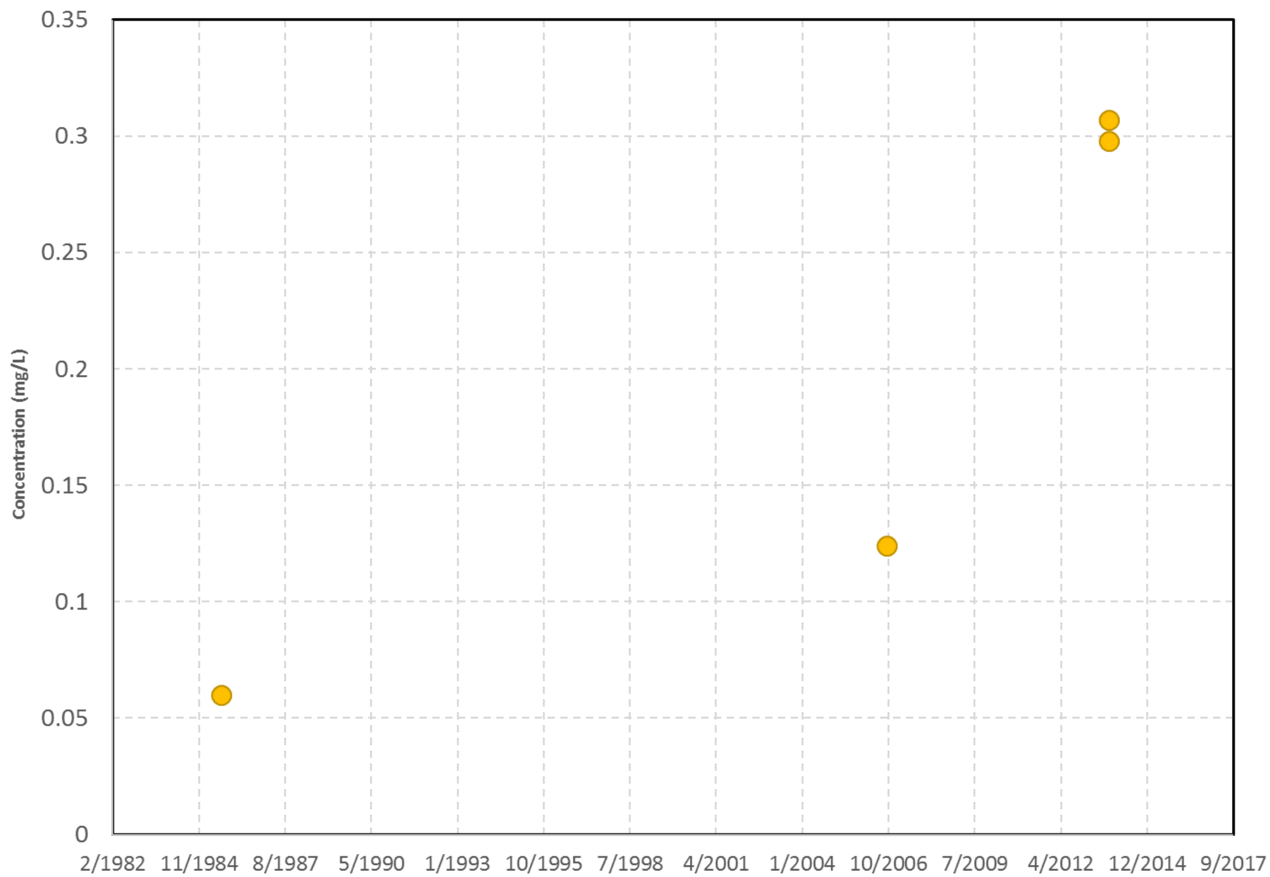


Figure 50. Barium (dissolved) concentration versus time for Station 5

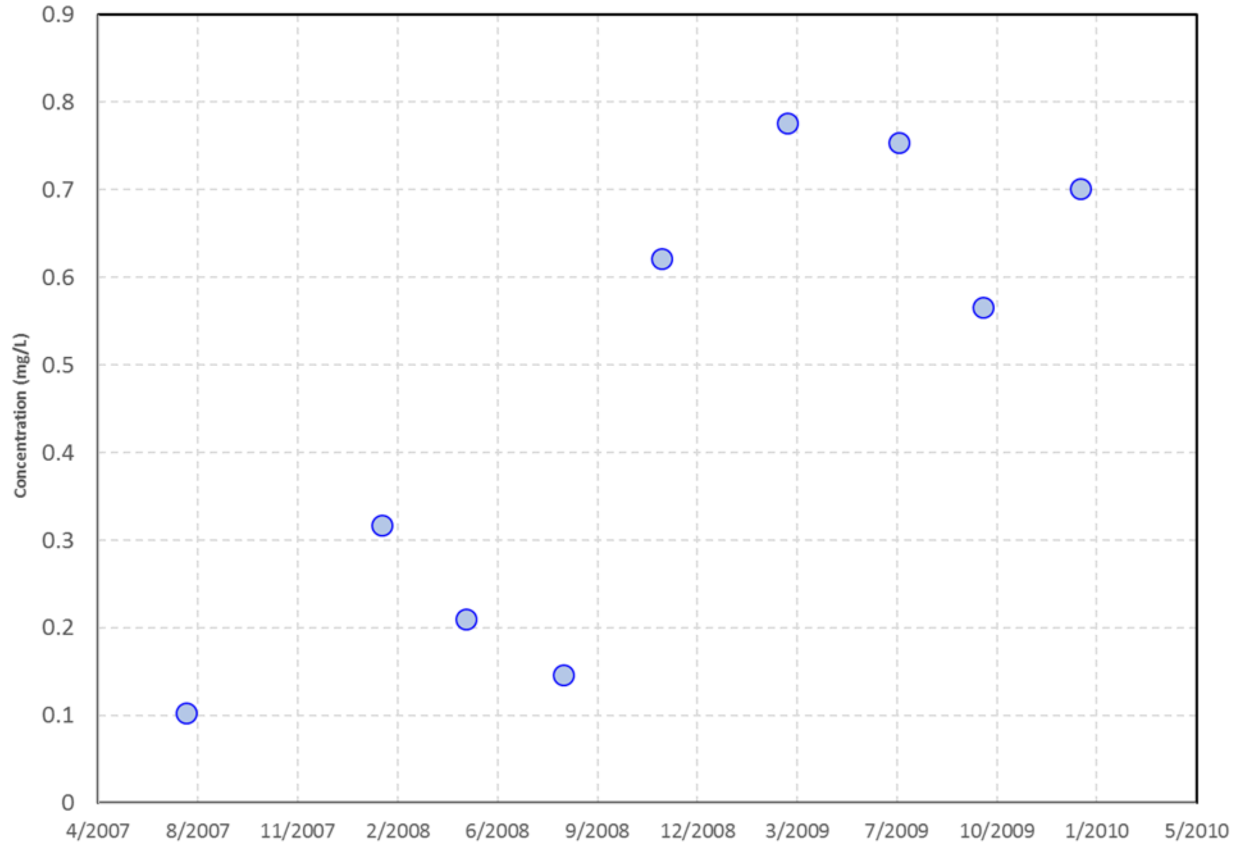


Figure 51. Barium (total) concentration versus time for Station 293

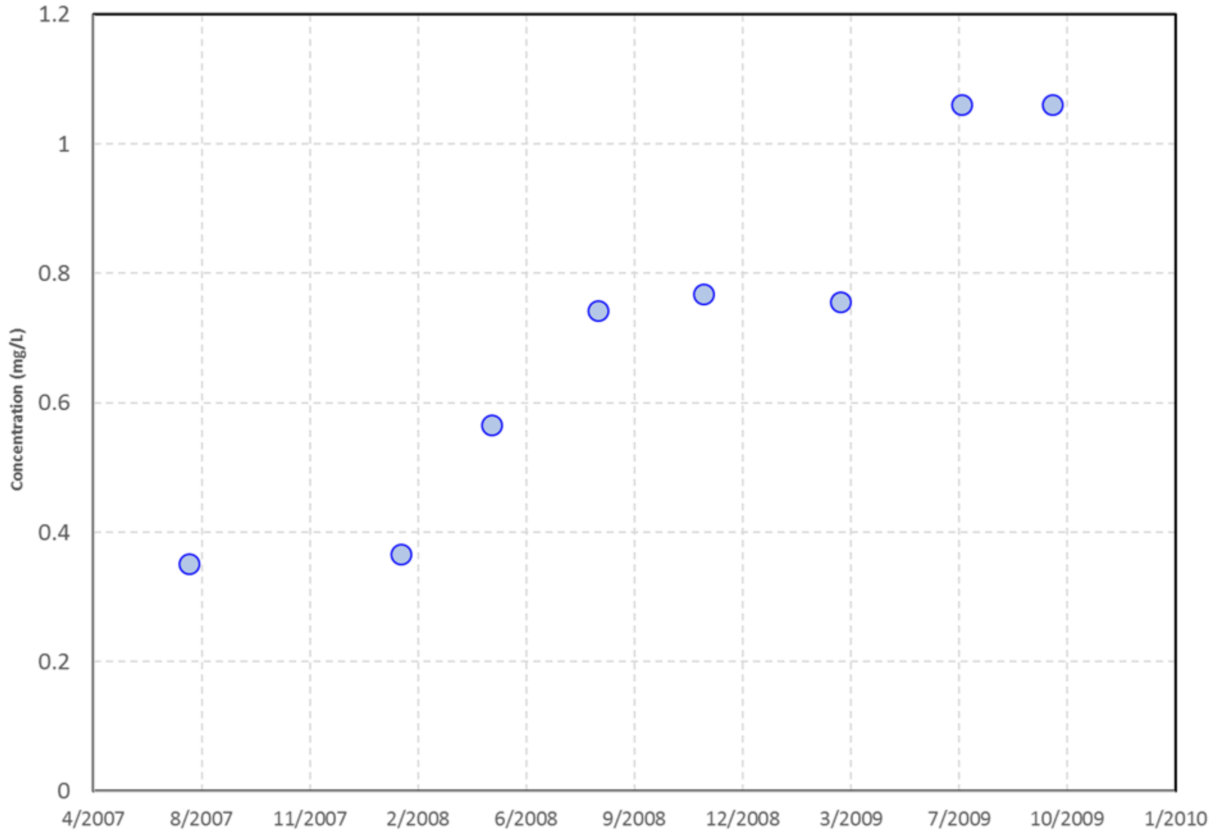


Figure 52. Barium (total) concentration versus time for Station 296

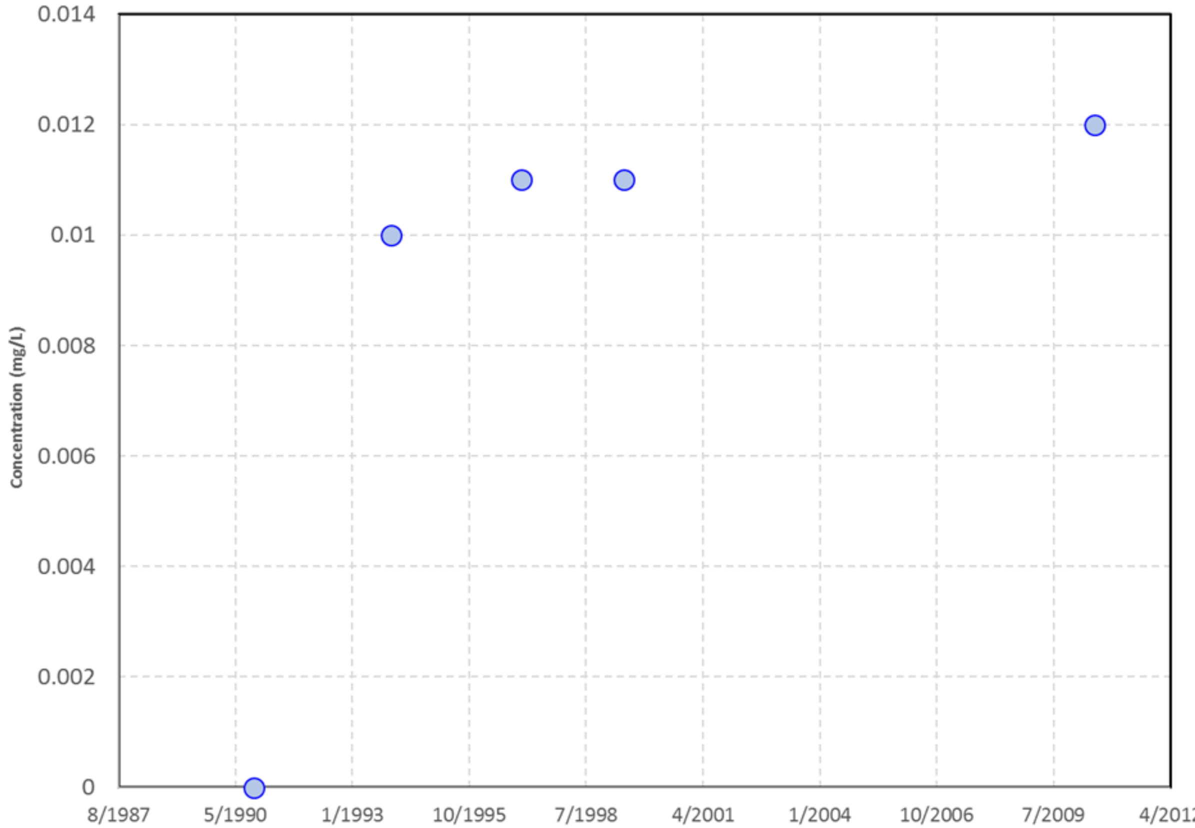


Figure 53. Barium (total) concentration versus time for Station 246

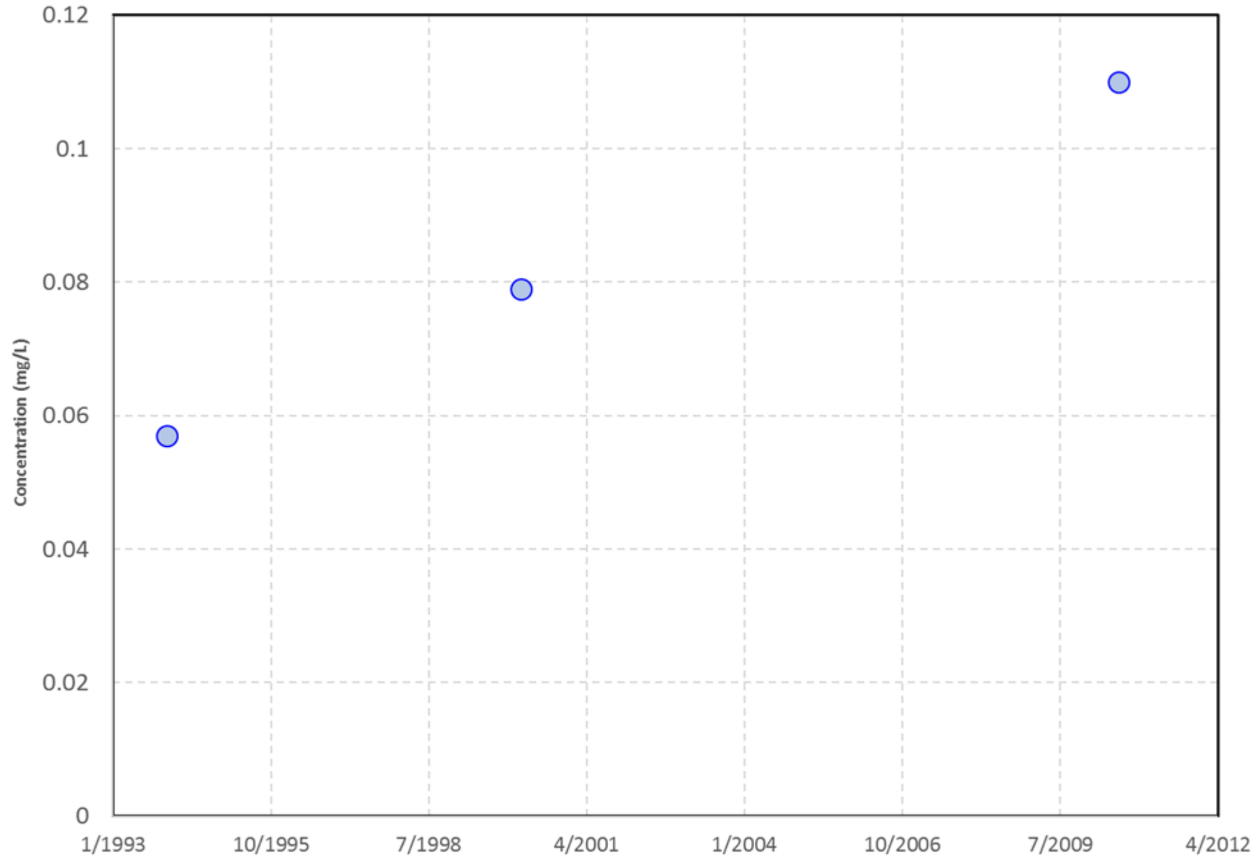


Figure 54. Barium (total) concentration versus time for Station 247

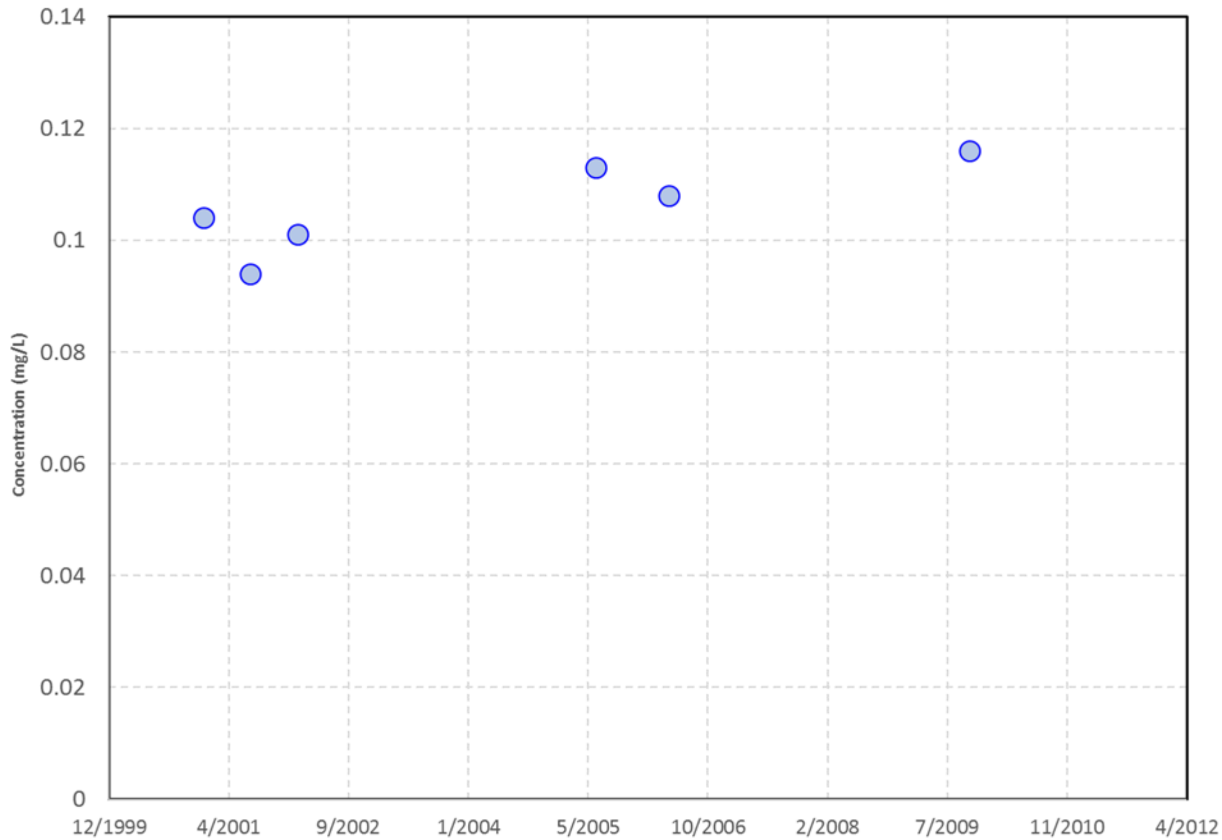


Figure 55. Barium (total) concentration versus time for Station 239

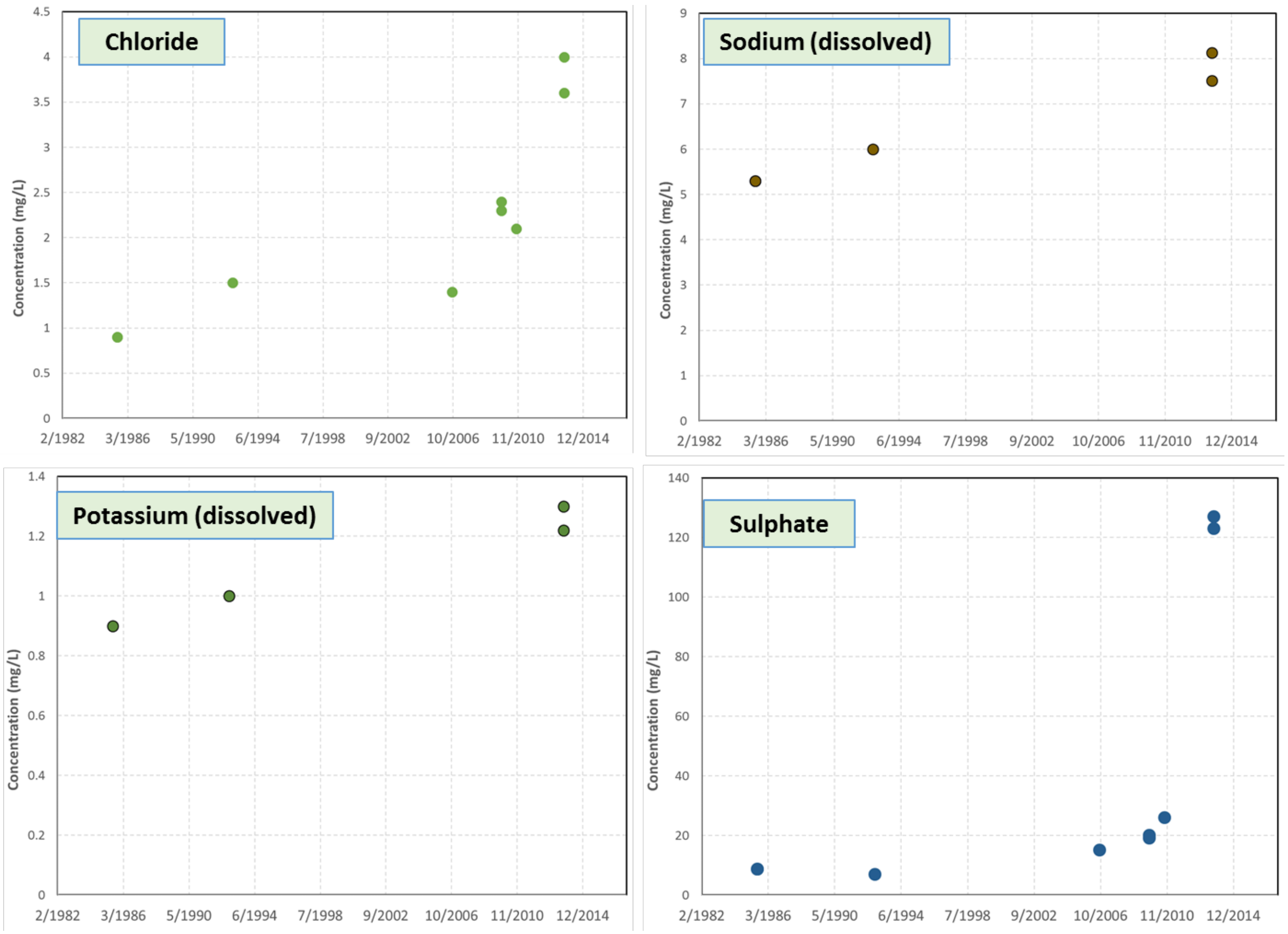


Figure 56. Chloride, sodium, potassium, and sulphate concentration vs time for Station 5 (provincial monitoring well # 286)

H. Conclusions

Based on the work completed, GW Solutions draws the following conclusions:

General conclusions

1. GW Solutions has constructed a database for the PRRD region from publicly available data by sorting, formatting and standardizing available surface water and groundwater quality data.
2. Access to data on surface water and groundwater is difficult in the PRRD. What has been achieved through this project should improve public access to water related information.
3. Quality control protocols such as electro-neutrality were used to select and verify the quality and reliability of the water quality data.
4. GW Solutions has compared the results to applicable provincial and federal guidelines.
5. GW Solutions has analyzed the data to classify the water samples per water type, based on the presence of the major ions dissolved in the water. At the regional scale, the water appeared to originally be predominantly calcium-bicarbonate for surface water and calcium/sodium-bicarbonate/sulphate for the groundwater samples.
6. Groundwater and surface water are intimately connected. Groundwater is a key contributor to surface water in periods of low flow and droughts. Should groundwater quality deteriorate, it will affect the quality of the surface water.
7. The lack of information on water, both on quality and quantity prior to the 1970s has prevented the definition of the baseline before human activities started having a footprint both at the surface and in the subsurface.
8. Data review has revealed the absence of adequate temporal and spatial monitoring of both surface water and groundwater prior to and concurrent with human activities that may impact water. A proper surface water and groundwater monitoring plan is urgently needed. It should monitor the following:
    a. springs;
    b. streams;
    c. lakes;
    d. wetlands;
    e. unconfined overburden aquifers;

   f. confined overburden aquifers;
   g. bedrock aquifers; and
   h. the intermediate zone.

9. An adequate set of each of these water bodies should be selected to have a proper spatial distribution.
10. Sampling and analyses has to be completed on a yearly basis, from mid-summer to early fall. The plan should be carried out for a duration of at least 10 years.
8. The monitoring plan should be adequately planned and funded.

Surface water

1. The database includes a total of 11,935 surface water samples from 364 locations collected between 1955 and 2014.
2. The parameters for which concentrations exceed the provincial guidelines are listed in Table 10.
3. The parameters for which concentrations exceed the federal guidelines are listed in Table 11.
4. GW Solutions has used Water Quality Indexes (WQI) to assign values indicative of their water quality to samples. The WQIs have been used to illustrate the water quality at stations over selected time periods. Maps have been produced illustrating whether the water quality is poor to excellent for the region and for each watershed.
5. The change in WQI has been used to estimate the improvement or worsening of the water quality over time. Maps have been produced illustrating WQI trends for the region and for each watershed. The trends for the region, using both provincial and federal guidelines, are shown in Figure 17 and Figure 21. They appear to indicate a general worsening of the water quality versus time.
6. After 2000 we observe an increasing presence of chloride, sodium and sulphate in surface water.

Groundwater

1. The database includes a total of 875 groundwater samples from 522 locations collected between 1943 and 2015.
2. The parameters for which concentrations exceed the provincial guidelines are listed in Table 12.
3. The parameters for which concentrations exceed the federal guidelines are listed in Table 13.
4. We observe an increasing presence of sodium and sulfate in groundwater (after 2000), and in spring water (after 2011), and we also observe an increase in mineralization of the groundwater from bedrock wells after 2011 (i.e., the major ions are present at a higher concentration). However, we cannot draw the conclusion that there has been an increase over time because we don’t have the dataset from the same wells. This confirms the need to build a dataset over time for selected monitoring locations.
5. Barium concentration has increased in groundwater at several locations over a relatively short time period. Such an increase is not expected under natural conditions. The observed increase in barium concentrations in groundwater could possibly be a result of the intense drilling activity in the region, through mobilization of deep groundwater containing higher concentration of barium and/or the release of barium into the shallow aquifers during drilling via drilling fluids. For Station 5 (provincial monitoring well # 286), the concentration of chloride, sodium, potassium, and sulphate has also increased over the same time period. Further investigation is required to determine the cause of the observed changes in concentrations.
6. The groundwater regime has been very poorly monitored and is still very poorly monitored. Aquifers need to be adequately characterized and monitored.
7. There is a profound absence of knowledge about the presence and migration of fluids in the intermediate zone of the subsurface, approximately located between 500 m and 2 km depth. This needs to be addressed in the areas of intense oil and gas activities. Adequate characterization and monitoring programs need to be designed and implemented very rapidly.

Table 10. Surface Water - % Samples Exceeding Provincial Guidelines

Parameters	Surface Water - % Samples Exceeding Provincial Guidelines				
	Freshwater Aquatic Life	Drinking Water	Livestock	Irrigation	Wildlife
Aluminum (Dissolved)	11%	3%			
Aluminum (Total)			4%	4%	4%
Arsenic	4%		1%	1%	1%
Boron			14%	1%	
Cadmium (Dissolved)	78%				
Cobalt	0.1%				
Copper	3%	0.1%	0.3%	0.3%	0.3%
Iron (Dissolved)	10%				
Iron (Total)	28%				
Lead	2%	1%	0.2%	0.2%	0.2%
Mercury		4%	4%	4%	8%
Molybdenum			0.1%	0.1%	0.1%
Selenium	7%	1%	0.4%	1%	7%
Silver	1%				
Zinc	4%		0.04%	0.1%	
Chloride		0.1%		0.2%	
Fluoride	0.1%	0.1%			0.1%
Sulphate		1%	0.4%		
Chlorophyll A	3%				
Nitrate		0.1%			

Parameters	Surface Water - % Samples Exceeding Provincial Guidelines				
Nitrite	0.1%				
Total Phosphorus	33%	29%			
Dissolved Oxygen	26%				

(Note: Coloured cell indicates threshold is defined for guideline – White cell indicates there is no defined threshold – blank coloured cell indicates no sample had concentration above threshold for specific guideline)

Table 11. Surface Water - % Samples Exceeding Federal Guidelines

Parameters	Surface Water - % Samples Exceeding Federal Guidelines			
	Freshwater Aquatic Life	Drinking Water	Livestock	Irrigation
Aluminum total	56%	56%	4%	4%
Antimony		11%		
Arsenic	20%	11%	10%	3%
Barium		0.3%		
Boron				2%
Cadmium	59%	9%	0.04%	9%
Chromium		0.5%		
Cobalt			0.05%	20%
Copper	44%		0.1%	0.3%
Iron	50%	50%		9%
Lead	50%	9%	6%	0.2%
Manganese		20%		5%
Mercury	56%	22%	22%	

Parameters	Surface Water - % Samples Exceeding Federal Guidelines			
Molybdenum	0.05%			19%
Nickel	12%			0.1%
Selenium	28%	0.4%	0.4%	9%
Silver	24%			
Thallium	11%			
Uranium	1%	0.5%		1%
Vanadium			0.2%	0.2%
Zinc	12%			
Calcium			0.07%	
Chloride	0.2%			
Fluoride	12%	0.1%		0.1%
Sodium		0.2%		
Sulphate			0.4%	
Nitrate	0.1%	0.4%		
Nitrite	2%			
Phosphorus			0.1%	
pH	2%	6%		
Total Dissolved Solids		7%	0.2%	7%

Table 12. Groundwater - % Samples Exceeding Provincial Guidelines

Parameters	**Groundwater - % Samples Exceeding Provincial Guidelines**				
	Freshwater Aquatic Life	**Drinking Water**	**Livestock**	**Irrigation**	**Wildlife**
Aluminum (Total)			0.2%	0.2%	0.2%
Arsenic	34%		3%	0.2%	3%
Boron	1%			12%	
Cobalt	1%				
Copper	17%	2%	2%	4%	2%
Iron (Dissolved)	66%				
Iron (Total)	24%				
Lead	0.4%	1%	1%		1%
Molybdenum		0.3%	1%	1%	1%
Selenium	4%				4%
Zinc	4%	0.2%	1%	0.2%	
Chloride		1%		3%	
Fluoride	1%	3%	2%	2%	3%
Sulphate		15%	9%		
Nitrate	1%	1%	1%		1%
Nitrite	1%	1%	1%		1%
Dissolved Oxygen	94%				

Table 13. Groundwater - % Samples Exceeding Federal Guidelines

Parameters	Groundwater - % Samples Exceeding Federal Guidelines			
	Freshwater Aquatic Life	Drinking Water	Livestock	Irrigation
Aluminum total	3%	4%	0.2%	0.2%
Antimony		1%		
Arsenic	34%	17%	3%	0.2%
Barium		6%		
Boron	0.2%			12%
Cadmium	1%	1%		1%
Cobalt				1%
Copper	49%	1%	2%	4%
Iron	40%	40%		7%
Lead	15%	2%	1%	
Manganese		56%		26%
Mercury	4%			
Molybdenum	1%			9%
Nickel	2%			
Selenium	10%			
Thallium	1%			
Uranium	1%	1%		3%
Vanadium			1%	1%
Zinc	26%	0.2%		2%
Chloride	3%	1%		1%
Fluoride	48%	2%	5%	5%
Sodium		33%		
Sulphate		15%	9%	

Parameters	Groundwater - % Samples Exceeding Federal Guidelines			
Nitrate	6%	2%		
Nitrite	5%	1%	1%	
Phosphorus	11%			
pH	4%	6%		
Total Dissolved Solids		56%	5%	56%

I. Recommendations

The following recommendations were passed at the August 25, 2016 PRRD Committee of the Whole meeting:

1. That the Board acknowledges and affirms that it is the Province who is ultimately the steward and regulator for water in the Province of BC, and that the Province recognizes that the quantity and quality of our water supply is essential to public health and sustainable communities, and that, the PRRD has received the report regarding the studies done on watersheds in the Peace, which will be posted for public use.
2. That the newly developed database be presented to appropriate regulators and provincial decision makers and request that, in collaboration with the PRRD, a review of all updated information be completed biannually in order to continue with trend analysis.
3. That the Province be encouraged to share with the public, all new water information in a timely manner.
4. That the Province, through the North East Water Strategy Working Group (a working group that includes input of local knowledge on water initiatives), determines at risk watersheds or parts of watersheds and conducts further assessment to identify causes and create mitigation strategies.
5. That the BC Ministry of Environment and the Ministry of Forests, Lands and Natural Resource Operations be requested to create regulations to characterize and monitor the movement of fluids in the intermediate zone between the depths of 500 meters and 2,000 meters.
6. That the Province be requested to implement monitoring programs to continue to define water baselines both for quantity and quality in areas of the region that are poorly defined or monitored.
7. That the PRRD host three public meetings to communicate these recommendations and any advancements on them.

J. Limitations

This report was prepared for the PRRD and T8TA. In evaluating the available information, GW Solutions has relied in good faith on information provided by others.

The produced graphs, images, and maps, have been generated to visualize results and assist in presenting information in a spatial and temporal context. The conclusions and recommendations presented in this report are based on the review of information available at the time the work was completed, and within the time and budget limitations of the scope of work.

The findings and conclusions documented in this report have been prepared for the specific scope of work of this project, and have been developed in a manner consistent with that level of care normally exercised by hydrogeologists currently practicing under similar conditions in BC.

GW Solutions makes no other warranty, expressed or implied, and assumes no liability with respect to the use of the information contained in this report, for other than its intended purpose. Any use which a third party makes of this report, or any reliance on or decisions to be made based on it, are the responsibility of such third parties. GW Solutions accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this report. All third parties relying on this report do so at their own risk. Electronic media is susceptible to unauthorized modification, deterioration and incompatibility and therefore no party can rely upon the electronic media versions of GW Solutions report or other work product. GW Solutions is not responsible for any unauthorized use or modifications of this report.

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GW Solutions makes no other representation whatsoever, including those concerning the legal significance of the information provided, or as to other legal matters touched on in this report, including, but not limited to, ownership of any property, or the application of any law to the facts set forth herein.

If new information is discovered during future work, including sampling, predictive geochemistry or other investigations, GW Solutions should be requested to re-evaluate the conclusions of this report and to provide amendments, as required, prior to any reliance upon the information presented herein.

K. Acknowledgement

This project could not have started nor been completed without the support of many people. GW Solutions expresses its gratitude to:

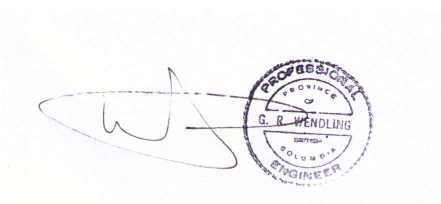
- Staff and directors of the PRRD;
- The BC Real Estate Foundation;
- Treaty 8 Tribal Association;
- The reviewers from BC Ministry of Forest, Lands, Natural Resources and Operation, Simon Fraser University, and the Oil and Gas Commission.

This project was completed with support and expertise provided by Interraplan, and Hoggan and Associates. Thank you Nancy McHarg and Reg Whiten.

L. Closure

This report was prepared by personnel with professional experience in the fields covered. Reference should be made to the General Conditions and Limitations attached in Appendix 13.

Yours truly,
GW Solutions Inc.



Gilles Wendling, Ph.D., P.Eng.
President

M. References

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Appendices

General

Appendix 1: Water quality guidelines

Surface water

Appendix 2: Water type results for all the watersheds within the PRRD

Appendix 3: Methodology for calculating water quality index WQI

Appendix 4: Water quality index results for all the watersheds using the CCME aquatic life guideline

Appendix 5: Water quality index results for all the watersheds using the BCMOE aquatic life (acute) guideline

Appendix 6: Scatter plot for all the surface water stations across the PRRD presented by watershed

Appendix 7: Parameter trend results

Groundwater

Appendix 8: Water type for the groundwater database

Appendix 9: Water quality exceedance analysis using Federal guidelines

9.1. Aquatic Life
9.2. Drinking Water
9.3. Agriculture-livestock
9.4. Agriculture-irrigation
9.5. Summary of exceedance over four periods of sampling
a) samples taken prior to 2001,
b) samples taken between 2001 and 2005,
c) samples taken between 2006 and 2010, and
d) samples taken between 2011 and 2015.

Appendix 10:Water quality exceedance analysis using BCMOE provincial guidelines

10.1. Aquatic Life
10.2. Drinking Water
10.3. Agriculture-livestock
10.4. Agriculture-irrigation
10.5. Wildlife exceedance
10.6. Summary of exceedance over four periods of sampling
  a) samples taken prior 2001,
  b) samples taken between 2001 and 2005,
  c) samples taken between 2006 and 2010, and
  d) samples taken between 2011 and 2015.

Appendix 11: Scatter plot per aquifer and stations

11.1. Aquifer scatter plot
11.2. Stations scatter plot

Appendix 12: Parameter trend results

Appendix 13: GW Solutions Inc. General Conditions and Limitations

APPENDIX 13

GW SOLUTIONS INC. GENERAL CONDITIONS AND LIMITATIONS

This report incorporates and is subject to these "General Conditions and Limitations".

1.0 USE OF REPORT

This report pertains to a specific area, a specific site, a specific development, and a specific scope of work. It is not applicable to any other sites, nor should it be relied upon for types of development other than those to which it refers. Any variation from the site or proposed development would necessitate a supplementary investigation and assessment. This report and the assessments and recommendations contained in it are intended for the sole use of GW SOLUTIONS's client. GW SOLUTIONS does not accept any responsibility for the accuracy of any of the data, the analysis or the recommendations contained or referenced in the report when the report is used or relied upon by any party other than GW SOLUTIONS's client unless otherwise authorized in writing by GW SOLUTIONS. Any unauthorized use of the report is at the sole risk of the user. This report is subject to copyright and shall not be reproduced either wholly or in part without the prior, written permission of GW SOLUTIONS. Additional copies of the report, if required, may be obtained upon request.

2.0 LIMITATIONS OF REPORT

This report is based solely on the conditions which existed within the study area or on site at the time of GW SOLUTIONS's investigation. The client, and any other parties using this report with the express written consent of the client and GW SOLUTIONS, acknowledge that conditions affecting the environmental assessment of the site can vary with time and that the conclusions and recommendations set out in this report are time sensitive. The client, and any other party using this report with the express written consent of the client and GW SOLUTIONS, also acknowledge that the conclusions and recommendations set out in this report are based on limited observations and testing on the area or subject site and that conditions may vary across the site which, in turn, could affect the conclusions and recommendations made. The client acknowledges that GW SOLUTIONS is neither qualified to, nor is it making, any recommendations with respect to the purchase, sale, investment or development of the property, the decisions on which are the sole responsibility of the client.

2.1 INFORMATION PROVIDED TO GW SOLUTIONS BY OTHERS

During the performance of the work and the preparation of this report, GW SOLUTIONS may have relied on information provided by persons other than the client. While GW SOLUTIONS endeavours to verify the accuracy of such information when instructed to do so by the client, GW SOLUTIONS accepts no responsibility for the accuracy or the reliability of such information which may affect the report.

3.0 LIMITATION OF LIABILITY

The client recognizes that property containing contaminants and hazardous wastes creates a high risk of claims brought by third parties arising out of the presence of those materials. In consideration of these risks, and in consideration of GW SOLUTIONS providing the services requested, the client agrees that GW SOLUTIONS's liability to the client, with respect to any issues relating to contaminants or other hazardous wastes located on the subject site shall be limited as follows:

(1) With respect to any claims brought against GW SOLUTIONS by the client arising out of the provision or failure to provide services hereunder shall be limited to a maximum of $20,000, whether the action is based on breach of contract or tort;

(2) With respect to claims brought by third parties arising out of the presence of contaminants or hazardous wastes on the subject site, the client agrees to indemnify, defend and hold harmless GW SOLUTIONS from and against any and all claim or claims, action or actions, demands, damages, penalties, fines, losses, costs and expenses of every nature and kind whatsoever, including solicitor-client costs, arising or alleged to arise either in whole or part out of services provided by GW SOLUTIONS, whether the claim be brought against GW SOLUTIONS for breach of contract or tort.

4.0 JOB SITE SAFETY
GW SOLUTIONS is only responsible for the activities of its employees on the job site and is not responsible for the supervision of any other persons whatsoever. The presence of GW SOLUTIONS personnel on site shall not be construed in any way to relieve the client or any other persons on site from their responsibility for job site safety.

5.0 DISCLOSURE OF INFORMATION BY CLIENT
The client agrees to fully cooperate with GW SOLUTIONS with respect to the provision of all available information on the past, present, and proposed conditions on the site, including historical information respecting the use of the site. The client acknowledges that in order for GW SOLUTIONS to properly provide the service, GW SOLUTIONS is relying upon the full disclosure and accuracy of any such information.

6.0 STANDARD OF CARE
Services performed by GW SOLUTIONS for this report have been conducted in a manner consistent with the level of skill ordinarily exercised by members of the profession currently practicing under similar conditions in the jurisdiction in which the services are provided. Engineering judgement has been applied in developing the conclusions and/or recommendations provided in this report. No warranty or guarantee, express or implied, is made concerning the test results, comments, recommendations, or any other portion of this report.

7.0 EMERGENCY PROCEDURES
The client undertakes to inform GW SOLUTIONS of all hazardous conditions, or possible hazardous conditions which are known to it. The client recognizes that the activities of GW SOLUTIONS may uncover previously unknown hazardous materials or conditions and that such discovery may result in the necessity to undertake emergency procedures to protect GW SOLUTIONS employees, other persons and the environment. These procedures may involve additional costs outside of any budgets previously agreed upon. The client agrees to pay GW SOLUTIONS for any expenses incurred as a result of such discoveries and to compensate GW SOLUTIONS through payment of additional fees and expenses for time spent by GW SOLUTIONS to deal with the consequences of such discoveries.

8.0 NOTIFICATION OF AUTHORITIES
The client acknowledges that in certain instances the discovery of hazardous substances or conditions and materials may require that regulatory agencies and other persons be informed and the client agrees that notification to such bodies or persons as required may be done by GW SOLUTIONS in its reasonably exercised discretion.

9.0 OWNERSHIP OF INSTRUMENTS OF SERVICE
The client acknowledges that all reports, plans, and data generated by GW SOLUTIONS during the performance of the work and other documents prepared by GW SOLUTIONS are considered its professional work product and shall remain the copyright property of GW SOLUTIONS.

10.0 ALTERNATE REPORT FORMAT
Where GW SOLUTIONS submits both electronic file and hard copy versions of reports, drawings and other project-related documents and deliverables (collectively termed GW SOLUTIONS's instruments of professional service), the Client agrees that only the signed and sealed hard copy versions shall be considered final and legally binding. The hard copy versions submitted by GW SOLUTIONS shall be the original

documents for record and working purposes, and, in the event of a dispute or discrepancies, the hard copy versions shall govern over the electronic versions. Furthermore, the Client agrees and waives all future right of dispute that the original hard copy signed version archived by GW SOLUTIONS shall be deemed to be the overall original for the Project. The Client agrees that both electronic file and hard copy versions of GW SOLUTIONS's instruments of professional service shall not, under any circumstances, no matter who owns or uses them, be altered by any party except GW SOLUTIONS. The Client warrants that GW SOLUTIONS's instruments of professional service will be used only and exactly as submitted by GW SOLUTIONS. The Client recognizes and agrees that electronic files submitted by GW SOLUTIONS have been prepared and submitted using specific software and hardware systems. GW SOLUTIONS makes no representation about the compatibility of these files with the Client's current or future software and hardware systems.

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Provided independently from this report and will be posted on the PRRD website