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BASELINE SURFACE WATER QUALITY IN THE PETITOT RIVER BASIN AND SURROUNDING WATERSHEDS: **EXAMINING POTENTIAL IMPACTS OF SHALE GAS DEVELOPMENT IN THE HORN RIVER BASIN, BRITISH COLUMBIA**

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BASELINE SURFACE WATER QUALITY IN THE PETITOT RIVER BASIN AND SURROUNDING WATERSHEDS: **EXAMINING POTENTIAL IMPACTS OF SHALE GAS DEVELOPMENT IN THE HORN RIVER BASIN, BRITISH COLUMBIA**

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EXECUTIVE SUMMARY

Quantifying change in the aquatic environment is a crucial component to studying the effects of resource development. A necessary first step to quantify change is the establishment of baseline and reference conditions. Information gathered in reference aquatic environments is particularly useful as it can assist in defining natural spatial and temporal variation of water quality condition (Meybeck et al. 1996).

As part of a three year study funded by Environment and Climate Change Canada and Natural Resources Canada (ecoENERGY Innovation Initiative, project UOSGQ963; http://www.nrcan.gc.ca/energy/funding/current-funding-programs/eii/4985) data were gathered to assess and monitor water quality conditions in northeastern British Columbia (BC). Defined in this report as portions of the Petitot, Fort Nelson, and Hay River basins, northeast BC is a region subject to both historical conventional oil and gas development and more recent unconventional oil and gas (UOG) development. UOG development in this area is presently focused on the Horn River Basin, Cordova Embayment and Liard Basin shale formations (BCOGC 2010, 2013a). Otherwise, UOG development in BC is centered in the Montney play, located further south (Adams et al. 2016).

Surface water quality assessment and monitoring focused on two river basins in this area: the Petitot River Basin and the Fort Nelson River Basin. Baseline and/or best available surface water quality information was gathered from January 2012 to March 2015. Benthic macroinvertebrates were collected over the same period to complement the water quality study through development of a Canadian Aquatic Biomonitoring Network (CABIN) bioassessment model.

The report is divided into three sections:

Part A, Routine Water Quality Monitoring study objectives were to gain a better understanding of water quality conditions in the Petitot River Basin by collecting baseline data using a standard suite of physical-chemical variables and establishing a representative long-term site. Routine water quality sampling sites were selected at locations with known exposure to UOG activity and varying watershed areas; submersible loggers were also installed to collect specific conductance and temperature data. Results indicate that water in the Petitot River Basin is generally hard with elevated levels of dissolved organic carbon. Most chemical variables analysed were below applicable water quality guidelines. Cadmium and iron exceedances were related to high sediment loads during freshet and from wetlands and groundwater during low flow periods. Routine monitoring did not detect any large scale impacts from UOG activities in the Petitot River Basin. Long-term monitoring has been rationalized to an accessible site that is representative of the basin (Petitot River at Highway 77) and incorporated into the federal-provincial long-term water quality monitoring network. Data are available at http://data.gc.ca.

Part B, Synoptic Water Quality Monitoring study objectives were to establish patterns of spatial and temporal water chemistry through synoptic water sampling at high and low flow periods and examine potential relationships between UOG activity and surface water quality. Sample sites were selected at microbasin drainage outlets to represent a range of upstream activity and potential contamination. A series of samples were also collected along the mainstem Petitot River at 20-kilometre intervals from the Alberta border to the Highway 77 bridge to capture potential "step-changes" in water chemistry as the river flows through the northeast BC gas production area. Patterns in water chemistry in the mainstem Petitot River showed no indication of upstream contaminants. In the smaller watersheds, there were potential indications of the effects on surface water chemistry of upstream UOG activity. Barium especially showed a relationship in freshet conditions with BC Oil and Gas Commission (BCOGC) Geographic Information System variables related to drill waste, though further work would be needed for a full and proper assessment. Trace organic analyses showed undetectable or low background concentrations for all measured analytes. Preliminary assessment of naphthenic acids across a range of UOG activity was inconclusive; further investigation may be warranted. Data are available at http://data.gc.ca.

Part C, Biological Monitoring study objectives were to establish baseline reference conditions based on benthic macroinvertebrate communities and habitat characteristics, and develop a predictive bioassessment model to assess the ecosystem health of streams in the Liard, Fort Nelson, and Petitot River basins exposed to UOG activity. The biological monitoring study design followed CABIN sampling methodology for benthic macro-invertebrate collections in streams and rivers (Environment Canada 2012, http://www.ec.gc.ca/rcba-cabin). Sampling was conducted at 53 reference sites unaffected or minimally influenced by human activity. Thirty five test sites were also selected across a gradient of UOG activity, based on well densities. A preliminary predictive bioassessment model for northeast BC was established and is available through the CABIN website for future assessment of water quality and ecosystem health in the region. Model assessment found that nearly two thirds of test sites were outside of the 90% threshold, suggesting that the biological community is different than what would be expected if there was no environmental stress on the ecosystem. However, the differences were not correlated with any of the BCOGC geospatial stressor variables. In addition, most water quality variables at most test sites were within the range of those measured at reference sites. Further assessment is required to determine the cause of divergence, but it is possible that climate related hydrological fluctuations may have provided a confounding effect on the stream ecosystems during the short duration of this study; continued temporal monitoring in reference areas will be critical to better understand this relationship.

At the initiation of the project, limited surface water quality monitoring information specific to UOG development in northeast BC were available. The data gathered here will contribute to an improved understanding of water quality and regional ecosystem health in the Petitot, Fort Nelson and Hay River basins. Baseline information generated as part of this project will inform the design of expanded monitoring in the area and in other shale gas plays, and support resource management decisions.

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INTRODUCTION

1. UNCONVENTIONAL OIL AND GAS DEVELOPMENT & HYDRAULIC FRACTURING

New technological developments in horizontal drilling and hydraulic fracturing have advanced the development of unconventional oil and gas (UOG) reserves in low-permeable formations across North America (Vidic et al. 2013). Hydraulic fracturing in UOG reserves involves drilling vertically miles below the surface into low permeability formations then drilling horizontally and injecting highly pressurized fluids (Figure 1). The fluid injection generates conditions which fracture the surrounding hydrocarbon rich rock, releasing otherwise tightly held gas that is collected at surface well-heads (BCOGC 2011, USEPA 2011).

FIGURE 1. *An aerial view of a winter drilling operation in northeast BC. Photo by Beverly McNaughton.*

Several types of waste are generated as part of the well preparation and hydraulic fracturing processes. These include drilling waste (which can be solids and/or liquids), hydraulic fracturing fluids, flow-back, and produced waters (see section 3.2 for definitions).

Fracturing fluids are largely fresh water with a suite of chemical additives often comprising 0.5 – 2% of the total volume (CSUG 2011). The additives may include acids, surfactants, gels and biocides (Soeder and Kappel 2009, Kargbo et al. 2010a) to facilitate injection, and proppants (e.g. sand) to maintain the produced cracks. A summary of typical fracturing fluid additives and their role in the hydraulic fracturing process can be found in British Columbia Oil and Gas Commission (BCOGC; BOCOGC 2012) and United States Environmental Protection Agency (USEPA; USEPA 2015). Waxman et al. (2011) reported that the most commonly used chemicals in hydraulic fracturing operations in the United States between 2005 and 2009 included methanol, isopropyl alcohol, 2-butoxyethanol and ethylene glycol. Regular use of benzene, toluene, xylene, ethyl benzene and naphthalene was also reported. In British Columbia, the mandatory disclosure of hydraulic fracturing fluids by well was required as of January 1, 2012 (BCMEM 2011). This information, including fluid purpose, ingredients, and concentrations, is available through the Canadian FracFocus website (http://fracfocus.ca/).

2. UNCONVENTIONAL OIL AND GAS DEVELOPMENT IN THE HORN RIVER BASIN, BRITISH COLUMBIA

Northeastern British Columbia (BC) is a region subject to both historical conventional oil and gas development and more recent UOG development. Approximately 86% of wells drilled in BC are centered on unconventional gas plays in northeast BC (Adams et al. 2016) including the Horn River Basin, the Cordova Embayment, the Montney and the Liard Basin (Figure 2) (BCOGC 2010, 2013a). Drilling in northeast BC typically extends 1,500 m to 4,000 m below the surface, and is then continued horizontally 2,500 m or more once the target formation is reached (BCOGC 2013a). Unconventional well pads are spaced several kilometres apart as one pad can accommodate up to 21 wells (Rivard et al. 2014) resulting in less total surface disturbance for UOG activity than conventional development.

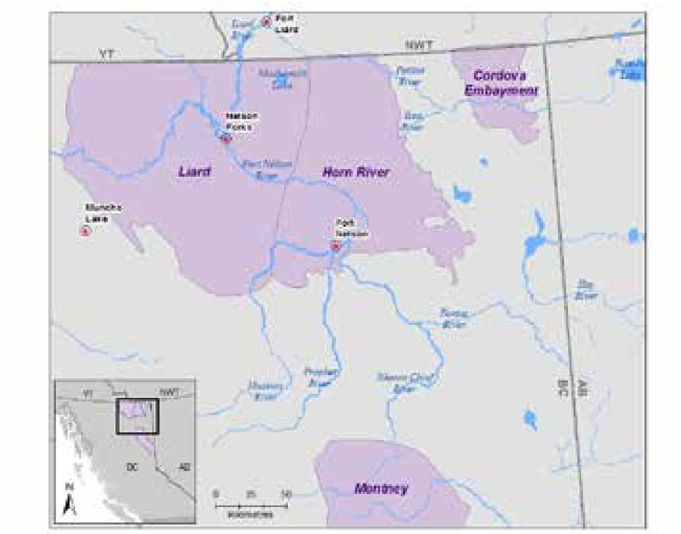


FIGURE 2. *Map of shale gas plays and major river systems in northeast BC (plays outside of provincial border are not illustrated).*

Estimates place the Horn River Basin deposit among the largest in North America and a focus of the Canadian shale gas industry (BCMEM-NEB 2011, Geoscience BC 2011). Unconventional shale gas exploration and development began in the Horn River Basin as early as 2005 with horizontal multistage hydraulic wells beginning around 2007 (Johnson and Johnson 2012). Reported UOG activity in the Horn River Basin is relatively low, accounting for 10% of the total production in BC as of January 2013 (BCOGC 2013a), and lower than activity in the US (Table 1). According to a 2011 National Energy Board (NEB) report, shale gas drilling in the Horn River was slowing due to declines in market value; however, many companies reportedly maintained property tenures for potential expansion if financial conditions improve (NEB 2011).

TABLE 1. *Shale gas development area comparisons of basins, well activity, and water usage.*

	* BASIN AREA KM^2	** NUMBER OF WELLS	** MEAN WATER USAGE M^3/WELL
BC-Horn River Basin	**1,146**	**50**	**76,923**
BC-Montney (*Heritage + North play combined*)	**2,986**	**341**	**8,368**
BC-Liard Basin	**934**	**1**	**144**
BC-Cordova Embayment	**316**	**15**	**36,739**
PA-Marcellus Shale	***__240,000__	***__3758__	***__7,500-26,000__
AR-Fayetteville	***__23,000__	***__2834__	***__7,500-26,000__

* BCOGC (2013a) data reported for 2012
** BCOGC (2014) data reported for 2012
*** Entrekin et al. (2011) data as of 2010

3. POTENTIAL IMPACTS TO SURFACE WATERS FROM UNCONVENTIONAL OIL AND GAS ACTIVITY

Although a range of environmental impacts are expected in relation to UOG development (including impacts to air quality and ground water), this report summarizes surface water quality information, specifically for flowing water (lotic environment).

Impacts to surface waters resulting from UOG activity have been investigated elsewhere in North America, primarily the Marcellus Shale deposit in Pennsylvania, USA, and include effects on both water quality and quantity (Williams et al. 2008, Soeder and Kappel 2009, McBroom et al. 2012, Ferrar et al. 2013, Olmstead et al. 2013, Warner et al. 2013, Brantley et al. 2014). An examination of UOG development in the United States highlighted the impact of regionally-specific stressors and the need for localized monitoring, due to the wide variation in geology, geo-chemistry, and hydrology that occurs at shale gas plays (Mauter et al. 2014).

3.1 WATER QUANTITY

According to the USEPA, water use in hydraulic fracturing can be broken down into the following stages: acquisition, chemical mixing, well injection, produced waters, wastewater treatment, and waste disposal (USEPA 2011). Other activities such as well drilling also require water to lubricate equipment and remove drilled rock (CSUG 2011, USEPA 2011). In northeast BC, water use is facilitated through water licenses, short term water use/diversion approvals, water source wells, private agreements, and groundwater wells. In 2014 the majority of water use for hydraulic fracturing had freshwater sources (including rivers, lakes, dugouts or fresh ground water). Dugouts[1] account for the largest number of permitted water diversions, followed by rivers, while the highest actual water volumes used was from rivers (BCOGC 2015d).

Due to the characteristics of the Horn River Basin formation, slickwater is used which is a highly water consumptive form of fluid for hydraulic fracturing (Johnson and Johnson 2012, Rivard et al. 2014) and therefore water consumption is atypically high (Jiang et al. 2014, BCOGC 2015d). The total consumed water volume for the Horn River Basin was reported at almost 4 million cubic metres in 2012; 2013 and 2014 saw much lower consumption closer to 1.5 million cubic metres (BCOGC 2015d). In the vicinity of the Horn River Basin formation, the largest water volume drawn as a percent of mean annual runoff (0.62%) occurred in the Tsea River Basin (a sub-basin of the Petitot River), while the largest actual volume used in any one basin occurred in the Kiwigana River Basin (a sub basin of the Fort Nelson River) (BCOGC 2015d).

3.2 WATER QUALITY

Surface water quality may be affected by oil and gas activity through several pathways: spills and seepage during the transport, storage, and use of chemicals, produced waters, and waste, which may result in both surface and subsurface contamination; subsurface contamination resulting from failed well infrastructure with subsequent transmission to surface waters; and increased soil erosion and disturbance related to well and infrastructure construction and use (e.g., well pads, access roads and pipelines) (CCA 2014).

Produced water

Produced water is a combination of injected hydraulic fracturing fluids and formation water which returns to the surface. The initial waters are called "flowback" and will contain both fracturing fluid and formation water. Beyond the "flowback" period, the water that will be generated through the life of the well is exclusively formation water and is referred to as "produced" (USEPA 2015, Kondash et al. 2017). For the purpose of this document, all return waters (i.e. "flowback" and "produced") are referred to as produced waters since the distinction is somewhat subjective and the exposure risk to surface waters is the same. Produced waters contain elevated salinity, organics, metals, and naturally occurring radionuclides (Spellman 2013, USEPA 2015) resulting from a combination of drilling and hydraulic fracturing additives as well as contact with the underlying formation (Soeder and Kappel 2009, Kargbo et al. 2010b, Kondash et al. 2017). The USEPA identified and compiled data characterizing dissolved ion and trace metal variables in produced water from eight shale and tight formations in the United States, and the ranges are presented in Table 2 below.

In addition to the inorganic constituents, produced waters can contain a wide spectrum of organic components. For example, flowback waters at wells in Colorado contained dissolved organic carbon (DOC) up to 590 mg/L (Lester et al. 2015). This organic fraction is comprised of chemicals used in fracking fluids and their breakdown products, drilling fluids, and some shale-associated hydrocarbons (Orem et al. 2007). The USEPA (2015) presented a table of 100+ chemicals detected in produced water, including many polycyclic aromatic hydrocarbons (PAHs), organic acids, and alcohols.

TABLE 2. *General concentration ranges of chemical variables identified in produced waters (USEPA 2015).*

VARIABLE	CONCENTRATION RANGE FOR SHALE FORMATIONS
Bromide (mg/L)	**111 – 589**
Calcium (mg/L)	**317 – 9,680**
Chloride (mg/L)	**9,156 – 119,000**
Magnesium (mg/L)	**61 – 1,270**
Sodium (mg/L)	**3,758 – 61,500**
Sulphate (mg/L)	**71 – 660**
Boron (µg/L)	**4,800 – 116,000**
Barium (µg/L)	**4,800 – 2,224,000**
Iron (µg/L)	**7,000 – 96,000**
Manganese (µg/L)	**2,000 – 7,000**
Strontium (µg/L)	**27,000 – 1,695,000**

Note: Data summarized from Table E-4 Appendix E, Hydraulic Fracturing Drinking Water Assessment (USEPA 2015)

Infrastructure

Infrastructure related to UOG development includes pipelines, seismic lines, wells and access roads, as well as gas processing facilities, water treatment facilities, and camps. In addition to production wells, other drilled wells associated with UOG operations include source wells (to obtain usable water < 4 000 ppm total dissolved solids (TDS) for injection and hydraulic fracturing), disposal wells (for the disposal of produced waters into a subsurface formation, typically >800m depth in northeast BC (BCOGC 2015c), and injection wells (used to inject water into an oil pool to enhance recovery).

1 Dugouts are pits used to collect water from natural sources such as rainfall, snowmelt, or groundwater flow.

Research has shown that UOG development can affect sediment loads in surface waters around wells. Increased sediment yields (erosion) were seen from basins with well pads compared to surrounding land uses in Texas due to the increase in bare compacted surfaces associated with the construction of well pads, though erosion rates appeared to stabilize over time (Williams et al. 2008, McBroom et al. 2012). The presence and density of shale gas wells in one study basin also appeared to increase downstream TSS concentrations (Olmstead et al. 2013).

In BC, subsurface formation disposal is permitted for non-hazardous wastes (as defined by the Hazardous Waste Regulation, B.C. Reg 63/88, O.C. 268/88) resulting from oil and gas activities (BCOGC 2015a). In the Horn River Basin there is a history of deep well disposal of wastewaters related to oil and gas operations (Ferguson 2015). However, assessments of the potential effects of deep well disposal remain unknown due to the lack of monitoring data across this broad area (Ferguson 2015).

Saline fluids, which may include produced waters from hydraulic fracturing operations as well as saline source water, are provisionally stored in surface lined containment systems. Two types are authorized by the BCOGC: lined in-ground earthen containment ponds (generally only used for a period of one year) and lined above-ground walled storage systems. The use of unlined containment ponds for the purpose of storing saline fluid is not permitted in northeast BC (BCOGC 2015b).

Drill waste

Well drilling waste, including drill cuttings and cement returns, is disposed of in unlined earthen excavations referred to as sumps (BCOGC 2015a). If required by poor soil conditions, above-ground tanks and lined sumps are common alternative disposal methods. The BCOGC requires that sumps must be filled-in within one year after drilling has stopped, and any precipitation that falls into the sump while still open is considered drilling waste. Where non-hazardous drill-waste returns will not harden with time, disposal can occur via mix-bury-cover methods or landfill (BCOGC 2015a). Drilling mud waste from water-based drilling systems may be disposed of on-site via mix-bury-cover and land-spreading, a onetime application where drilling wastes are spread on the shallow subsoil of land and incorporated into the shallow subsoil.

Non-aqueous (oil or synthetic-based) drilling mud waste, commonly produced in northeast BC (Murray et al. 2009), may be discharged onto land provided constituents are not in high enough concentrations to be considered hazardous (B.C. Reg. 254/2005 O.C. 541/2005; (BCOGC 2015a). If it contains hazardous concentrations of hydrocarbons, the waste must be disposed of according to the Hazardous Waste Regulation (B.C. Reg. 63/88 O.C. 268/88) under the *Environmental Management Act* of British Columbia (BCOGC 2015a).

3.3 INCIDENTS AND INCIDENT REPORTING

In the United States, spills from well sites to the surrounding environment have been noted in Pennsylvania and Colorado, including chemicals, fracturing fluid and produced waters (USEPA 2015). The USEPA has estimated the frequency of onsite spills from Colorado and Pennsylvania ranged from 0.4 to 12.2 spills per hundred wells, based on investigating 151 fracturing fluids and chemicals and 225 produced water spills on or near a well pad between January 2006 and April 2012 (USEPA 2015). Results indicated that 30% of fracturing fluid spills came from storage units, while 74% of produced water spills were caused by a failure of container integrity. Additionally, 9% of the fracturing fluid spills reached surface waters and in 64% of these cases, fluids infiltrated the soil. None of the spills were reported to have reached groundwater (USEPA 2015). Data gathered by Brantley et al. (2014) from a publically accessible violations database also suggest the frequency of small incidents, including spills < 400 gallons, was high in the Marcellus Play area (Pennsylvania).

In BC, produced water is stored in double walled or bermed tanks or it is directly transported to a disposal well. Flowback is stored in double lined and fenced structures with leak detection and leachate collection or on-site storage tanks (Figure 3) for temporary storage (HRBPG 2010). Incidents are reported to the BCOGC, except when a pipeline is transboundary and regulation is the jurisdiction of the National Energy Board (NEB). For the study area in northeast BC, 335 incidents involving liquids were reported to the BCOGC between February 2000 and July 2015 (http://www.bcogc.ca/, accessed July 2015). In 27 incidents, spills were related to diesel fuel or other liquid hydrocarbons. The NEB received 2 incident reports involving liquids in northeast BC between 2008 and 2015 (http://www.neb-one.gc.ca, accessed June 2016). During the study period, nine incidents were reported, none involving diesel or other liquid hydrocarbons, with no incidents reported in 2012 (http://www.bcogc.ca/, accessed July 2015).

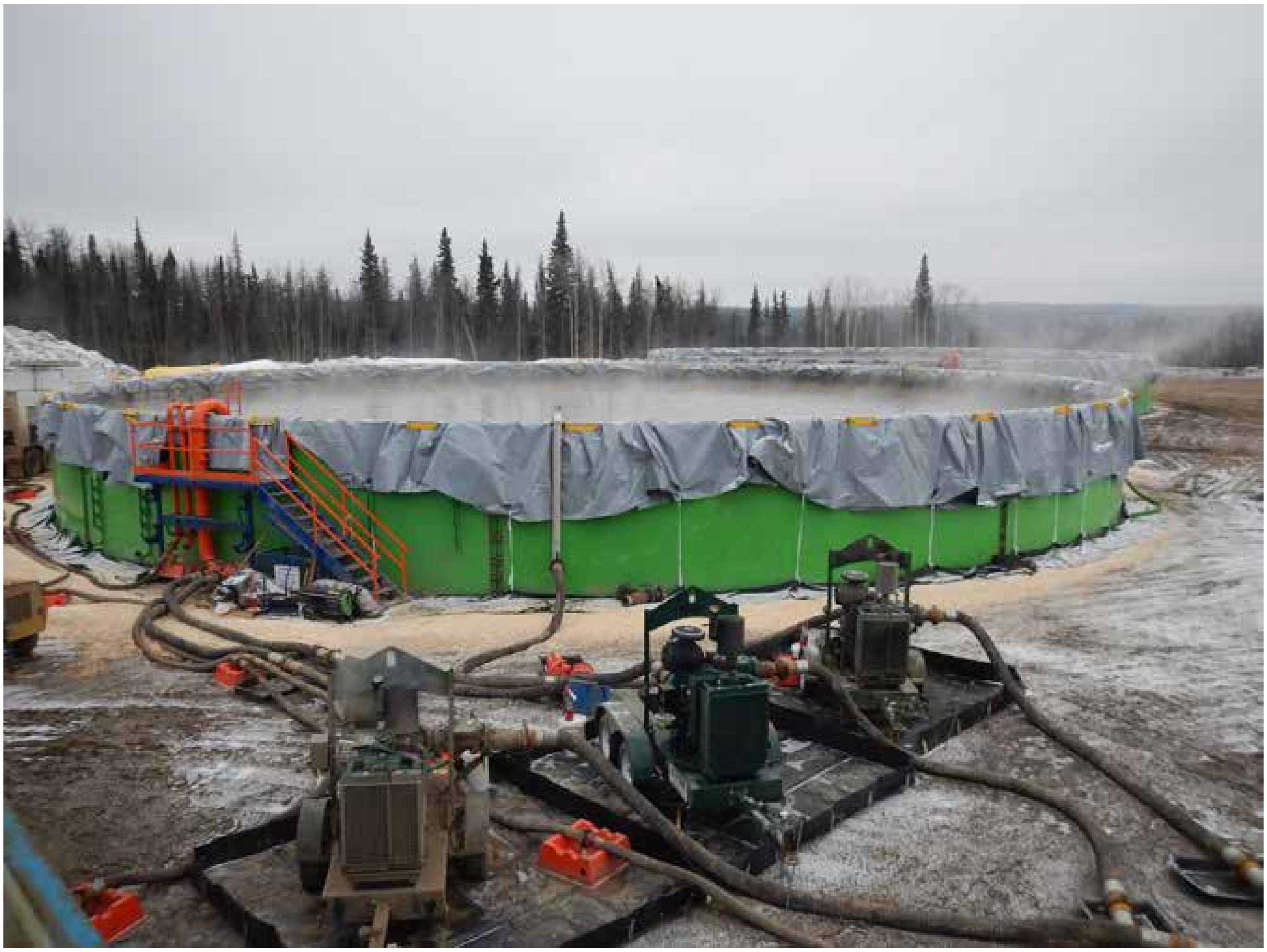


FIGURE 3. *Above-ground fluid storage at a well site in the Montney area. Photo by Patrick Shaw.*

4. STUDY AREA

The study area includes portions of the Petitot, Fort Nelson, and Hay River basins in northeast BC (Figure 4). Two major rivers flow through the area – the Fort Nelson River from the south and the Petitot River to the north. From Lake Bistcho in Alberta, the Petitot River meanders westward into BC and the Northwest Territories, joining the Liard River near the hamlet of Fort Liard, NT. The Fort Nelson River, located southeast of the Petitot River Basin, originates with the confluences of the Fontas and Sikanni Chief Rivers. The Fort Nelson River also joins the Liard upstream of the Petitot confluence, near Nelson Forks, BC.

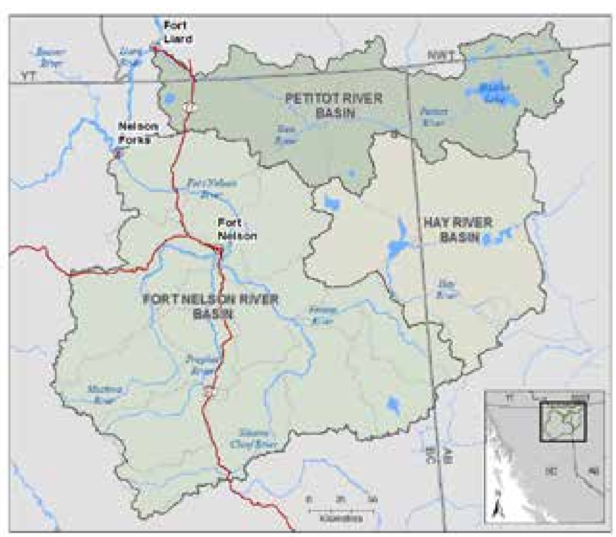


FIGURE 4. *Northeast BC study area showing the Petitot, Hay, and Fort Nelson River basins.*

The region is part of the Western Canada Sedimentary Basin, with regional bedrock geology consisting of limestones, shales and other sedimentary rocks. Most of the study area (>80%) is underlain by the Cretaceous Fort St John Group, comprised of mixed mudstone/siltstones. Midway between Fort Nelson and the Northwest Territory (NWT) border is an escarpment of the Dunvegan Formation,

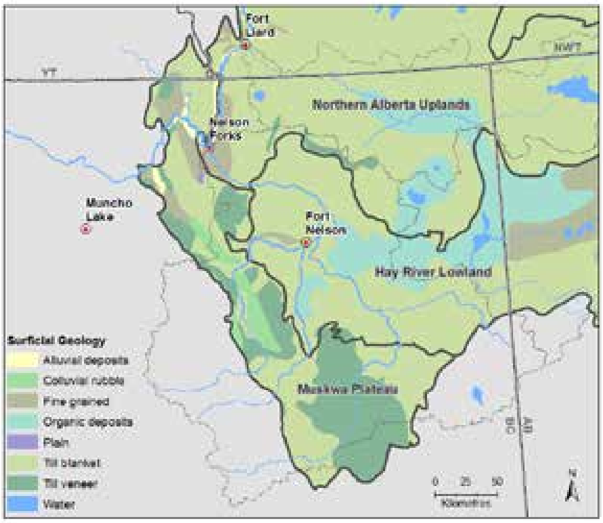


FIGURE 5. *Surficial geology for three primary ecoregions in northeast BC. Thick lines represent ecoregion boundaries; thin lines indicate boundaries of Hay, Petitot, and Fort Nelson River basins. For source information see Appendix Table C1.*

consisting of massive conglomerates, sandstones and shale, which directs water flow either north to the Petitot River Basin or south to the Fort Nelson River (Demarchi 2011).

Throughout the study area, till overlies glacially streamlined bedrock and glaciolacustrine and glaciofluvial deposits preserved in buried paleochannels (Figure 5; (Huntley et al. 2011)). These are highly weatherable, resulting in deeply-incised river valleys (to 150 m below average elevations) which can be a prominent regional feature (Ronneseth 1994). The poorly drained clay rich till on the plateaus and glaciolacustrine sediments in lowland areas are covered by extensive postglacial peat deposits and fens (Huntley et al. 2011). The region has low relief with patchy to widespread wetland referred to as muskeg. River flows tend to be stable and laminar in highly incised channels because of the muskeg dominated headwaters and low relief areas (Johnson 2010). Low topographic relief results in ponding and marsh development throughout, and highly sinuous creeks and rivers (Figure 6). Additionally, stream networks are disrupted by beaver activity and to a lesser extent roads, pipelines and other infrastructure (Huntley et al. 2011).

Land cover is predominately forested (~55%) with areas of extensive wetlands (~34%) made up of bogs and fens (Figure 7). Fens channel water off the landscape through lakes and streams while bogs function as reservoirs in isolation from groundwater and are only interconnected when the water table is high. Bogs represent the storage of water and regions of potential permafrost whereas fens interact with laterally flowing groundwater (Johnson 2010). Based on soil drainage types, conditions are imperfect to very-poorly-drained throughout the area. Dominant vegetation includes boreal white and black spruce, with black spruce and tamarack prevalent in poorly drained (Demarchi 2011). At higher elevations, shrubs such as willows, scrub birch and white spruce are more common (Demarchi 2011).

FIGURE 6. *Examples of sinuous creek development in low-relief and deeply-incised terrain typical in the Petitot River watershed. Photos by Patrick Shaw.*

FIGURE 7. *Wetland and marshy area near the Petitot River watershed. Photo by Patrick Shaw.*

The regional climate is continental, with cool, short summers and cold winters. In addition, pockets of permafrost may remain year-round, with the distribution and extent of these pockets dependent on annual winter temperatures (Demarchi 2011). Fort Nelson climate averages measured by Environment and Climate Change Canada (ECCC) are presented in Figure 8. Examining Fort Nelson climate data, Johnson (2010) found an approximate 10 year cyclical pattern to dryness severity that did not correspond with El Niño or La Niña weather events. The wettest years were 1948, 1957, 1962, 1977, 1984, 1988, 1997 and 2007. Currently, the climate is in a wetter phase with lake and river levels significantly higher than during drought years.

Surface water flows are dominated by a short snow-melt driven freshet, with a rapid return to base flows. Following snowmelt, lowland streams act like saturated catchments and respond rapidly to precipitation events. As water levels decline, stream discharge becomes increasingly dominated by bogs and fens. There are three main aquifers in the Fort Nelson Lowland which includes the Petitot, Hay and Fort Nelson River basins – an unconfined sand and gravel, a confined sand and/or sand and gravel, and a bedrock aquifer (Ronneseth 1994). Contributions from groundwater tend to remain relatively constant; most runoff is from surface water stored in peatland (Johnson 2010). A historical Water Survey of Canada gauging station, *Petitot River below Highway 77* (10DA001), just south of the BC-NWT border, was re-initiated in 2013. The nearby *Hay River near Hay River* station (07OB001) has hydrology similar to the Petitot River (Faria 2002). As a result, the hydrograph from the Hay River was used to review expected hydrometric conditions of the Petitot River during the period of this study (Figure 9).

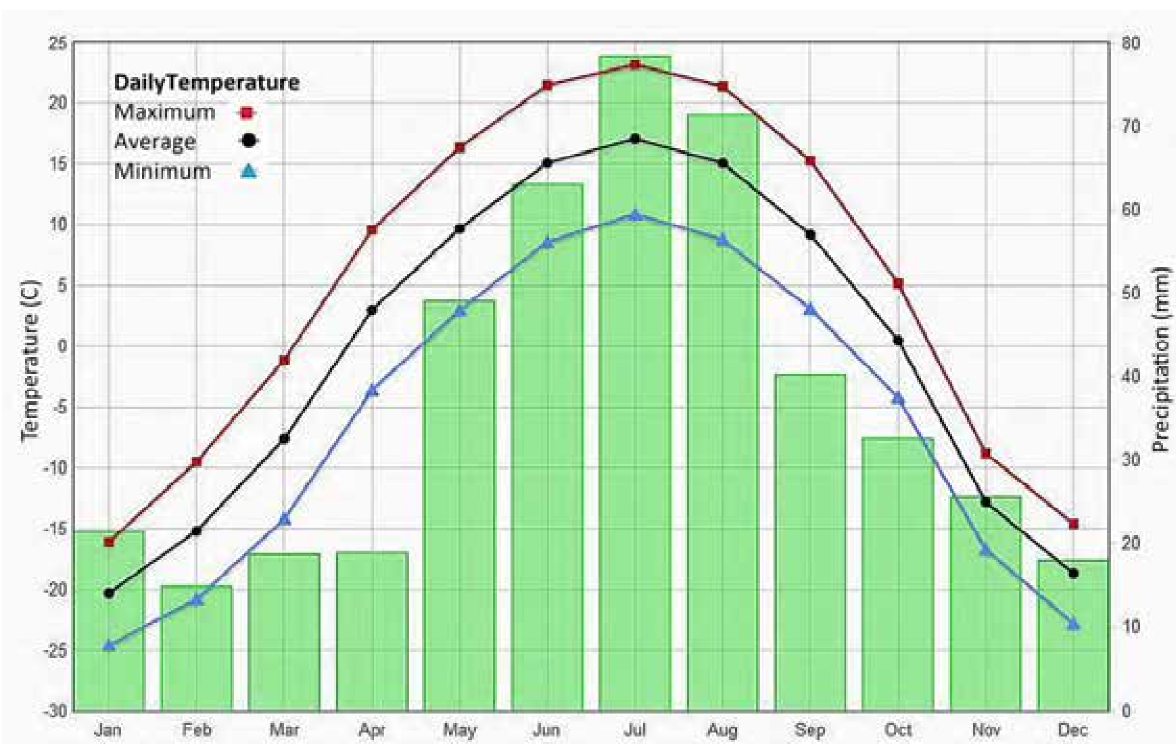


FIGURE 8. *Temperature and precipitation for 1981 – 2010 Canadian Climate Normals, Fort Nelson A. Data and graph from Water Survey of Canada* *http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html*

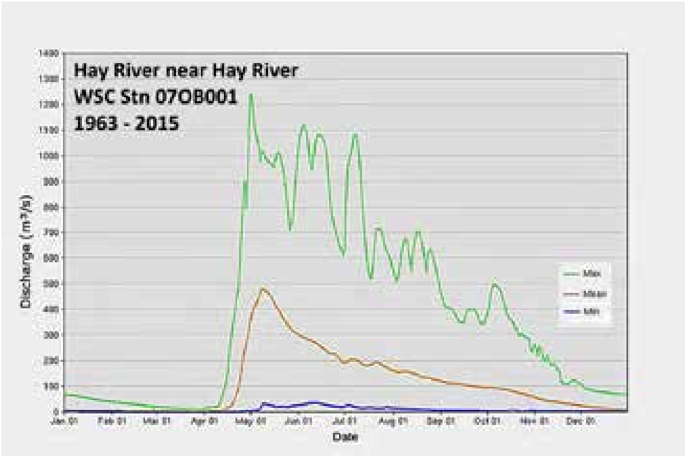


FIGURE 9. *Summary of historical daily discharge for the Hay River near the community of Hay River (07OB001), 1963-2015. Data and graph from Water Survey of Canada*

5. SITE SELECTION

As a starting point we used watershed delineations from the BC Ministry of Forests Lands Natural Resource Operations and Rural Development - GeoBC 1:50000 Freshwater Altas (Government of BC Data Catalogue, https://catalogue.data.gov.bc.ca/dataset). This is a province-wide Geographic Information System (GIS) layer of stream courses and delineated microbasins of sufficient detail to resolve first-order streams. Within ArcGIS 10.1 (ESRI, Inc.) the watershed layer was combined with GIS information compiled monthly and made available by the BCOGC (http://data-bcogc.opendata.arcgis.com) showing the location and type of industrial facilities – such as wells, abandoned wells, compressor stations, and waste disposal sites. Densities of wells within microbasins over the region were determined (Figure 10). Coordinates for basin downstream outlets were used in the initial site selection.

Once in the field, a high proportion of these possible sample sites were rejected based on access, ponded flows or low water levels. In many cases, the precise selected location had poor access, but an alternate site could be found by travelling some distance upstream or downstream of the original location.

There are several factors that affect infiltration and streamflow in the study area: low topographic relief, the presence of wetlands or muskeg and discontinuous permafrost. In low topographic relief areas total discharge is low because snow water is retained on the landscape and stored in the soils above permafrost and in wetlands in spring. Drainage is slow and infiltration occurs over broad areas because muskeg and discontinuous impermeable permafrost allow very little downward infiltration of water forming bogs, swamps, fens and marshes (Johnson 2010).

Using the final site coordinates, upstream watershed outlines were obtained using digital elevation data (DEM) in raster format, corresponding to the 1:50K NTS (25m cell size) map sheets. National Hydro Network data in vector format were obtained from the GeoBase data collections through the Government of Canada Open Data portal (http://open.canada.ca/en/open-data). After DEM conditioning the individual watersheds upstream of the sample points were delineated in ArcGIS (ESRI, Inc.) using the ArcHydro extension. Density of various gas facilities were recalculated using the newly delineated basins.

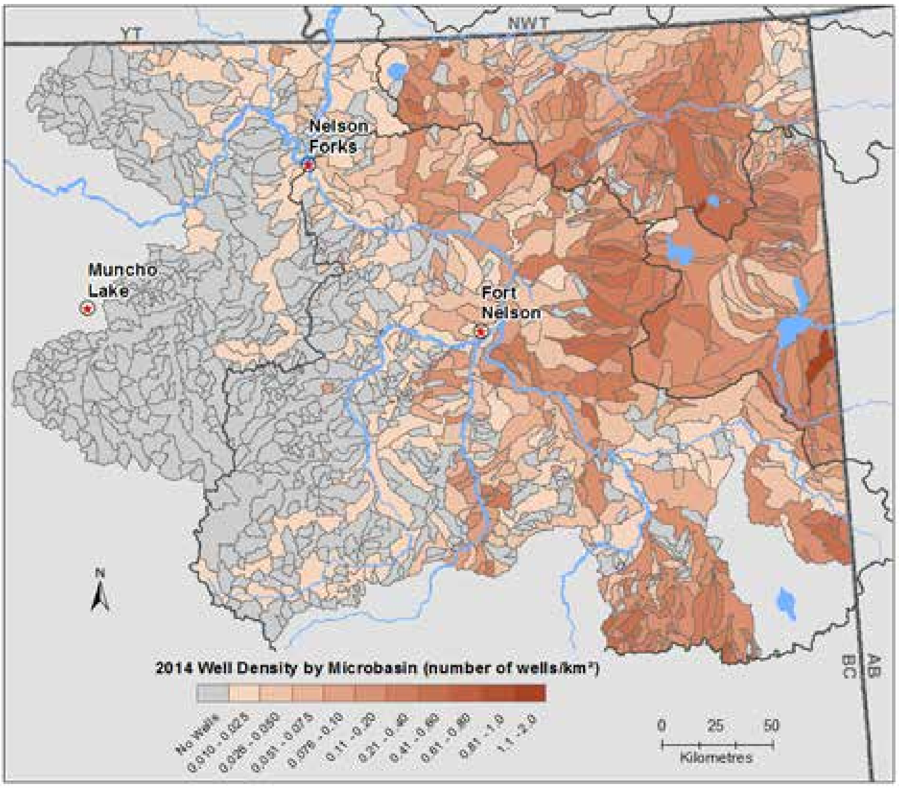


FIGURE 10. *Well density by microbasin within the defined study area based on 2014 geospatial data from BCOGC. The Petitot, Hay and Fort Nelson River basins are outlined overlapping the British Columbia, Alberta and Northwest Territory borders.*

6. STUDY OBJECTIVES

This project was divided into three components to assess and monitor surface water quality; objectives for each component are outlined below.

The objectives of **Part A, Routine Water Quality Monitoring**, were to a) gain a better understanding of water quality conditions in the Petitot River Basin by collecting baseline data using a standard suite of physical-chemical variables, and b) establish a representative long-term site in the Petitot River Basin.

The objectives of **Part B, Synoptic Water Quality Monitoring**, were to a) establish patterns of spatial water chemistry through synoptic water sampling at high and low flow periods, and b) examine potential relationships between UOG activity and surface water quality.

The objectives of **Part C, Biological Monitoring**, were to a) establish a reference condition bioassessment model based on benthic macroinvertebrate communities and habitat characteristics and b) assess the ecosystem health of streams in the Liard, Fort Nelson, and Petitot River basins exposed to UOG activity.

PART A
ROUTINE FRESHWATER QUALITY MONITORING

A1. METHODS

A1.1 STUDY DESIGN AND SITE SELECTION

Characterizing water quality in the study area relied on two sampling methods employed at each site: discrete water quality grab-sampling of surface waters and automated water quality sampling. Sampling sites were selected at locations with known exposure to UOG activity and varying watershed areas (Table A1) with access via road or helicopter. Grab-samples were collected quarterly and coincided with seasonal changes in the hydrograph. To capture episodic events like spills, submersible conductivity loggers monitored water quality continuously.

Two sites were sampled on the Petitot River mainstem and three were sampled on tributaries (Figure A1). Variable selection was consistent with the federal-provincial long-term water quality monitoring network in accordance with the Canada-British Columbia Water Quality Monitoring Agreement (Government of Canada 1985). Submersible loggers were also installed. The loggers collected specific conductance (SpCond) and water temperature data.

TABLE A1. *Basin characteristics for long-term water quality sites.*

SITE	TYPE	BASIN SIZE KM^2	WELLS	WELL DENSITY $WELLS/KM^2$	SUMP SITES
Petitot River Basin					
Fortune Creek	**Trib**	**197.6**	**14**	**0.071**	**5**
Emile Creek	**Trib**	**724.8**	**61**	**0.084**	**24**
Sahdoanah River	**Trib**	**1386**	**513**	**0.37**	**13**
Petitot River down-stream of Tsea River	**Main**	**15366**	**1246**	**0.195**	**57**
Petitot River at Highway 77	**Main**	**21188**	**1568**	**0.143**	**116**

Note: Trib = tributary site, Main = mainstem site

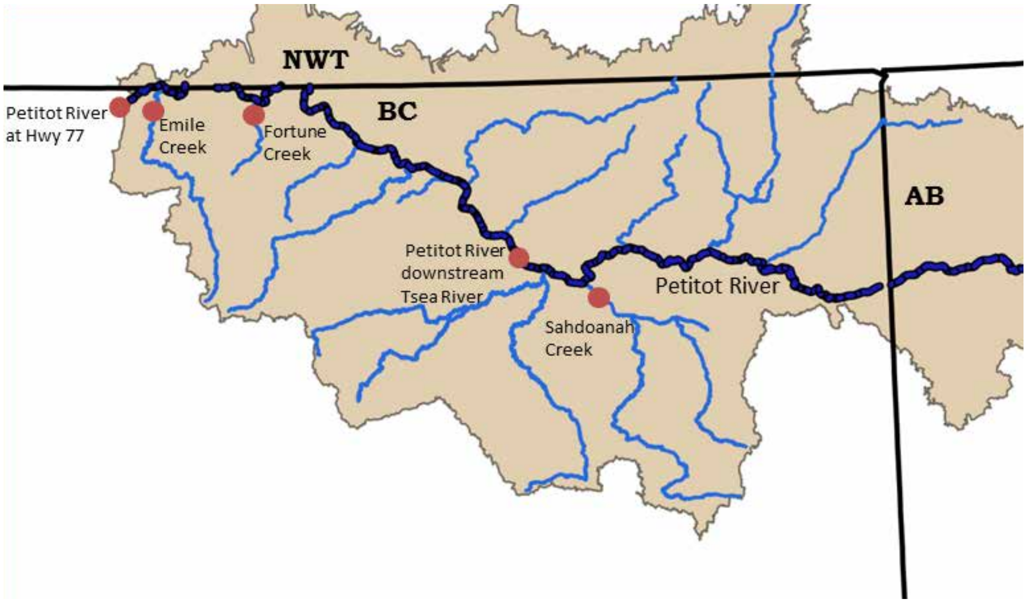


FIGURE A1. *Petitot River watershed showing location of routine water quality sampling locations.*

A1.2 SAMPLE COLLECTION

Water quality grab samples were collected quarterly between January 2012 and March 2015. During open water, samples were collected by wading and bottles were filled by hand according to Canadian Council of Ministers for the Environment (CCME) protocols (CCME 2011). Under winter ice conditions, samples were collected through ice using a manual ice auger and pumps according to CCME (CCME 2011) and Alberta protocols (Alberta Environment 2006). Field measurements including pH, SpCond, conductivity, and water temperature were recorded using an in situ multi-probe.

Samples were handled according to CCME protocol (CCME 2011) and shipped to the analytical laboratories as soon as possible after sample collection. Analyses for nutrients, major ions, and physical variables were conducted at Maxxam Analytics in Burnaby, BC and ECCC's Pacific and Yukon Laboratory for Environmental Testing in North Vancouver, BC. Metals and phosphorus analyses were conducted at the ECCC National Laboratory for Environmental Testing (NLET) in Burlington, ON. All laboratories used are Canadian Association for Laboratory Accreditation Inc. (CALA) accredited. Analytical methods used are outlined in Appendix A.

Submersible loggers (Figure A2) were installed in free flowing water in the main flow of the river or streams and set to record every 30 minutes. Equipment was only accessible during the open low-water season, typically August to October. Loggers were generally replaced in the fall and retrieved in July or August the following year. Loggers were placed in protective housings consisting of slotted 2-inch PVC pipe anchored to the stream bed

FIGURE A2. *HOBO® U24 (top) and Solinst LTC Levelogger® (centre). Photo by Patrick Shaw.*

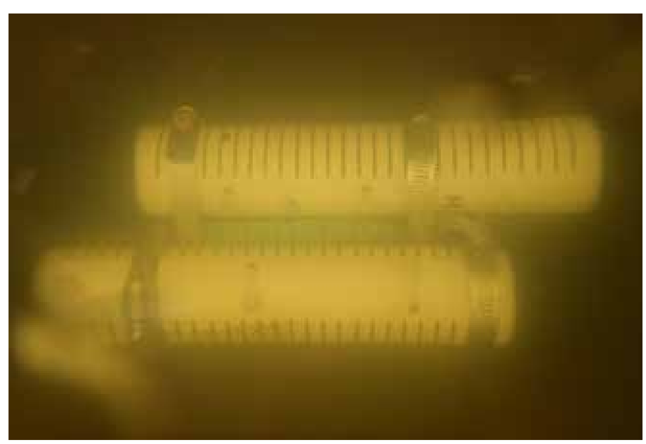


FIGURE A3. *Housing and typical conductivity logger installation. Photo by Ayisha Yeow.*

with rebar wickets (Figure A3). The slots allowed for water to flow freely through the pipe while keeping out pebbles and debris. Two types of conductivity loggers were tested for their abilities to withstand cold temperatures and river conditions in the study area: the Solinst LTC Levelogger® and HOBO® U24 Conductivity logger. A detailed comparison of logger properties is available in Appendix A.

Field quality assurance and quality control (QAQC) includes procedures and precautions to minimize bias and imprecision in the data generated. This project utilized five strategies for ensuring proper QAQC was followed for discrete sampling:

- Discrete and quality assurance samples were collected and handled according to CCME protocols for freshwater quality sampling (CCME 2011).
- Field instruments (YSI ProPlus™) were checked and calibrated prior to each trip.
- Equipment-blank samples were collected from the pump and tubing prior to each trip. Trip blank samples for each day were collected.
- Field replicate and field blank samples made up approximately 40% of the total samples.

Data loggers were checked and/or calibrated against standards before deployment according to manufacturing protocols. Field measurements were also collected using a YSI ProPlus™ probe *in situ* at the time of logger deployment and retrieval, to adjust for instrument drift and fouling.

Discrete sample data were validated according to the Data Approval Protocol (Environment Canada, 2014b) under the Canada – British Columbia Water Quality Monitoring Agreement (Government of Canada, 1985). Variables were also screened for data below method detection limits (i.e. censored data). Automated temperature data were validated using the data processing procedures outlined in (Toohey et al. 2014) with Aquarius Workstation version 3.1 (Aquarius version 3.1 (Aquatic Informatics Inc. 2013)). Additionally, patterns in the water temperature data were screened to determine possible periods where loggers were buried in sediment, encased in ice, or exposed to air were removed from further analysis, in which case data were removed.

A1.3 DATA ANALYSIS

All statistical analyses were performed in R version (R Core Team 2015). Box plots (ggplot2, Wickham (2009)) were calculated by site on a subset of variables where applicable guidelines were available and relevant to shale gas development. Summary statistics included median, maximum, minimum, sample size and first and third quartiles. Summary statistics were estimated using a robust Regression on Order Statistics method (Lee 2013) for variables with less than 80% censored data following quality screening (Helsel 2012).

Box plots provide a graphical representation of the summary statistics using all sample data by site and season. Quarterly seasons were defined based on the Hay River hydrograph (Section 4, Figure 9). Box plots show the median and lower and upper quartile values of the data. The lower and upper edges of the box represent the 25th and 75th quartiles while the lines represent 1.5 times the inner quartile range. The center line is the median concentration and the stars are outliers (Figures A4 and A5).

Non-parametric tests were used to evaluate differences between sites and seasons on data collected between January 2012 and March 2015. A Kruskal-Wallis Test was performed (H_o: equal medians of all groups) (Helsel 2012). If the null hypothesis was rejected, a Wilcoxon test of multiple comparisons using rank sums was applied for pair wise comparisons between specific sites. Significance values were adjusted to counter elevated Type 1 errors (Helsel 2012).

Box plots and time series plots for continuous logger data were generated using the ggplot2 package (Wickham 2009). Due to many issues arising with installations during the first year of data collection, data analysis was restricted to August 2014 to July 2015. A table showing the completeness of automated SpCond and water temperature data – percentage of days per month where greater than 80% of readings of the daily record are intact – is shown in Appendix A.

A2. RESULTS AND DISCUSSION

Discrete water quality samples collected from five sites provided point-in-time physical-chemical, metals, and nutrient information to generally characterize water quality conditions in the Petitot River Basin. Results were also compared to applicable water quality guidelines. Water quality in the Petitot River Basin can generally be characterized as medium hard, with a high buffering capacity (Table A2). High concentrations of total suspended solids (TSS) and metals (Table A2) were, with the exception of iron, mainly driven by spring freshet. The river was classified as mesotrophic having moderate phosphorus (P) levels (CCME 2004). The tea-like colour observed on tributaries in the basin is due to dissolved organic carbon (DOC) (Table A2). Individual site results and comparison to water quality guidelines can be found in Appendix A.

TABLE A2. *Median water quality in the Petitot River Basin (n=64), with guideline comparison where available. BC Water Quality Guidelines for the protection of aquatic life are presented unless otherwise indicated.*

VARIABLE	MEDIAN	GUIDELINE
Total Alkalinity (mg/L $CaCO_3$)	**82**	**20*****
Total Aluminium (µg/L)	**48.9**	**5000(Wildlife)**
Total Arsenic (µg/L)	**0.55**	**5**
Total Barium (µg/L)	**40.1**	**1000†**
Total Berylium (µg/L)	**0.0125**	**n/a**
Total Boron (µg/L)	**13.3**	**1200**
Total Bromide (mg/L)	**66% <DL**	**n/a**
Total Cadmium (µg/L)	**0.017**	**0.069-0.40‡**
Dissolved Calcium (mg/L)	**34**	**n/a**
Dissolved organic carbon (mg/L)	**19.55**	**n/a**
Dissolved Chloride (mg/L)	**1.3**	**600**
Total Chromium (µg/L)	**0.125**	**8.9‡**
Total Cobalt (µg/L)	**0.216**	**110**
Total Copper (µg/L)	**0.82**	**5.46 - 30.3***
Hardness (mg/L $CaCO_3$)	**116**	**n/a**
Total Iron (µg/L)	**593**	**1000**
Total Lead (µg/L)	**0.1055**	**22.9 - 332***
Total Lithium (µg/L)	**5.705**	**n/a**
Total Dissolved Solids (mg/L)	**181**	**500†**
Dissolved Magnesium (mg/L)	**7.17**	**n/a**
Total Manganese (µg/L)	**49.5**	**945 - 3857***
Total Molybedenum (µg/L)	**0.488**	**2000**
Nitrate (mg/L)	**0.0036**	**32.8**
Nitrite (mg/L)	**70% <DL**	**0.06-0.6****
pH	**7.95**	**6.5-9.0**
Total Phosphorus (µg/L)	**17.6**	**Framework‡**
Dissolved Potassium (mg/L)	**0.899**	**n/a**
Total Suspended Solids (mg/L)	**4.8**	**n/a**
Total Rubidium (µg/L)	**0.926**	**n/a**
Dissolved Sodium (mg/L)	**4.33**	**200†**
Total Selenium (µg/L)	**0.1**	**2**
Specific Conductance (µs/cm)	**224**	**n/a**
Total Strontium (µg/L)	**79.25**	**10,700§**
Dissolved Sulphate (mg/L)	**28.25**	**218 - 429***
Total Uranium (µg/L)	**0.3495**	**n/a**
Total Vanadium (µg/L)	**0.35**	**n/a**
Total Zinc (µg/L)	**1.15**	**33 - 191***

Note:
* BC Water Quality Guideline based on hardness
** BC Water Quality Guideline based on Cl concentration <2 mg/L
*** Environmental Quality Guidelines for Alberta Surface Water
† Health Canada Drinking Water Guideline
‡ Canadian Water Quality Guidelines for the Protection of Aquatic Life
§ Proposed by McPherson et al. (2014)
DL = detection limit

A2.1 GRAB SAMPLES: GENERAL WATER QUALITY CONDITIONS

Comparison to guidelines

Hardness (expressed as mg/L $CaCO_3$) in the Petitot River Basin ranged from 36.8 to 214 mg/L with a median value of 116 mg/L and generally the water is considered hard. Natural sources of hardness in water are sedimentary rocks and seepage or runoff from soils. A CCME or BC water quality guideline has not been established for hardness, however Health Canada has defined degrees of hardness for drinking water (Health Canada 1979): Soft water <60 mg/L, Medium hard water 60 – 120 mg/L, Hard water 120 – 180 mg/L and Very hard water >180 mg/L.

Alkalinity ranged from 22.3 to 261 mg/L with a median concentration of 82 mg/L. All results were above the recommended guideline of 20 mg/L (Alberta Environment 2014) for sensitive streams suggesting that the basin exhibits high buffering capacity to resist changes in acid inputs.

The pH ranged from 7.33 to 8.39 with a median pH of 7.95, slightly alkaline and within the acceptable range of the BC water quality guideline for pH (6.5 – 9.0) for the protection of aquatic life (McKean and Nagpal 1991). In a documented release of fracking fluids into Acorn Creek, Kentucky, pH was reduced from 7.5 to 5.6 (Papoulias and Velasco 2013); low pH (4.5 – 6) is harmful to aquatic insects, fish and amphibians.

Dissolved organic carbon ranged from 10.5 to 32.4 mg/L with a median concentration of 19.6 mg/L for the basin with much of the surface water exhibiting a tea-like colour. In natural conditions, DOC is the result of the decomposition of organic residues. Dissolved organic carbon is found in humic substances that can enter water bodies from soil and peat bogs. Higher concentrations are found in marshy and woodland areas (Chapman and Kimstach 1996). The BC guideline for protection of aquatic life recommends that the 30-day 50^{th}-percentile be within 20% of historical background levels (Moore 1998). Without historical DOC data a guideline comparison was not possible, however results can now be used as a baseline for future comparisons. Changes in DOC can cause reductions in primary productivity and system metabolism, while increasing susceptibility to toxic metals and acidification (Moore 1998).

Total suspended solids generally ranged from <1 to 328 mg/L (median = 4.8 mg/L) with the highest values occurring during freshet. The maximum value (328 mg/L) occurred on Fortune Creek during peak flow in 2013. No guideline comparison was possible as the current TSS guideline is based on changes relative to background concentration. However, the data from this study may be used for future considerations when setting background levels for the guideline. Total suspended solids in rivers typically increases as a function of flow and can vary dramatically. Pad construction, roadways and pipeline construction can lead to accelerated erosion and runoff which can increase TSS in streams. Total suspended solids in turn reduces available sunlight, raises water temperatures, decreases dissolved oxygen and clarity and ultimately damage the biological condition (Olmstead et al. 2013).

Nitrate (NO_3) concentrations ranged from <0.002 to 0.46 mg/L and 70% of nitrite (NO_2) results were below the method detection limit (0.002 mg/L). All measured NO_3 and NO_2 concentrations were below BC water quality guidelines. The most common form of nitrogen found in natural waters is NO_3, an essential nutrient to aquatic plants (Chapman and Kimstach 1996). Nitrite has been shown to be quite toxic to some groups of fish, particularly salmonids (Meays 2009).

Total Phosphorus concentrations ranged from 7.7 to 212 μg/L with the maximum values occurring during freshet. The current trophic status of the Petitot River Basin based on the median phosphorus value (17.6 μg/L) is mesotrophic and therefore defined as having moderate nutrient levels. Phosphorus is generally the limiting nutrient for algal growth and therefore controls the primary productivity of a water body (Chapman and Kimstach 1996); high levels of phosphorus can lead to eutrophication. Phosphorus is naturally occurring in most rocks, animal waste, plant material, and in the atmosphere. The CCME phosphorus guideline has a tiered-framework where concentrations should not exceed predefined trigger ranges nor increase more than 50% over the baseline (CCME 2004). The data from this study may be used to evaluate increases against background levels.

Total cadmium (Cd) (0.005 – 0.214 μg/L) exceeded the BC guideline at three of five sites in the Petitot River Basin during spring freshet in May 2013 (Table A5). The exceedances were likely related to high TSS concentrations. Additionally, 39% of samples from all sites exceeded the BC guideline for total iron of 1000 μg/L (Phippen et al. 2008). In BC, guidelines for Cd, copper (Cu), lead (Pb), manganese (Mn), and zinc (Zn) are based on hardness as these metals become more toxic in soft water. Trace amounts of metals are naturally present in freshwaters from the weathering of rocks and soils.

Seasonality

For analysis, data were separated into winter (January to March), spring (April to June), summer (July to September) and fall (October-December) seasons. A Kruskal-Wallis test was used to test for overall differences and the pairwise Wilcoxon test to determine which seasons were different. Most variables were significantly different during spring freshet in May (Figure A4). Dissolved organic carbon and uranium (U) did not show any significant differences between seasons. Total suspended solids and related variables (arsenic (As), Cd, iron (Fe), Mn, Zn, Pb) had significantly higher concentrations in the spring during freshet and variables such as alkalinity, hardness, boron (B), chloride (Cl), strontium (Sr), NO_3, sodium (Na) and SpCond were significantly higher during low flow periods in the winter (Appendix A). During low flow periods, stream flow is influenced by upstream bogs and fens controlled by discontinuous permafrost that dictates surface water-groundwater interactions. There is very little infiltration of water in the region because peat tends to have low vertical permeability. Drainage of peat causes increases in summer baseflow, suspended sediments, maximum stream temperature, specific conductance, pH, NO_3, calcium (Ca), magnesium (Mg) and Na concentrations (Johnson 2010).

Fortune, Emile and Sahdoanah creeks also exhibited elevated Fe concentrations during the winter (Appendix A). Again, these are likely influenced by upstream bog and fen areas that affect groundwater inputs to the streams during low flow periods. Depth, thickness and duration of ground frost and permafrost control subsurface flow, infiltration and recharge rates (Johnson 2010). Groundwater sampled from shallow wells in the Fort Nelson region contained up to 5 mg/L total Fe (Rosenneth 1994).

Between site comparisons

Hypothesis testing between sites was used to determine if there were any differences between high and low UOG activity sites or between the smaller and midsize tributaries and the mainstem Petitot River. Comparison of water quality conditions between sites was explored using the Kruskal-Wallis test for significant differences and the Wilcoxon pairwise test to determine which site(s) were different. Box plots were then created to provide a graphical representation of the differences between sites by variable.

Emile Creek and the two mainstem Petitot River sites (Petitot River at Highway 77 and Petitot River downstream of Tsea River) exhibited fairly similar water quality conditions based on the Kruskal-Wallis test. Median alkalinity, As, barium (Ba), Ca, Mg, hardness, molybdenum (Mo), U, SpCond were significantly lower in Fortune Creek than the other sites sampled in the Petitot River Basin (Figure A5). Sahdoanah Creek also had significantly higher concentrations of Fe and DOC compared to the mainstem Petitot sites and Fortune Creek (Figure A5) which may be a function of different upstream bog and fen areas between sites. For As, overall there was a significant difference between sites, however, the pairwise comparisons were not significant. Closer examination of the pairwise results shows Fortune Creek is different from Sahdoanah River and the mainstem Petitot River sites at $\alpha = 0.07$.

Fortune Creek exhibited many differences in water quality variables when compared to the other sites. It also has the smallest drainage area, the fewest number wells, disposal facilities and sump storage facilities in the basin. The differences in alkalinity, Ca, dissolved inorganic carbon (DIC), hardness, Mg and SpCond are likely a result of basin size. Rivers and streams with smaller drainage areas are more responsive to rain events and this will influence the water quality (Maybeck et al. 1996). The differences in As, Ba and U may reflect minor impacts related to the management of drill cuttings. Geochemical simulations of black shale drill cuttings with rainwater or landfill leachates under typical storage conditions suggest that carbonate or sulfide mineral dissolution could mobilize As and U (Phan et al. 2015). Drill cuttings in contact with soil could result in Ba accumulation and/or subsequent migration of Ba to groundwater (Phan et al. 2015). Options for disposal of drill waste (water-based mud systems) in northeast BC include either the construction of sumps or land spreading (BCOGC 2015a).

A2.2 GRAB SAMPLES: VARIABLES RELATED TO PRODUCED WATER

The USEPA compiled metal and dissolved ion data in produced water from eight shale and tight formations in the United States (USEPA 2015) which includes high concentrations of B, Ba, bromide (Br), Ca, Mg, Na, Cl, sulphate (SO_4), Fe, Mn, Sr and TDS. Comparisons to BC approved water quality guidelines for aquatic life were made where available. In the absence of BC approved guidelines results have been compared to CCME, Health Canada or USEPA guidelines. It is important to note that there are no guidelines for Br, Mg, Ca or Sr.

Boron

Total B concentration ranged from 3.9 to 46.2 µg/L in the Petitot River Basin with a median concentration of 13.3 µg/L, 90 times lower than the guideline (1200 µg/L, Moss and Nagpal (2003)). Warner et al. (2014) examined six types of water samples from 14 oil and gas formations and determined that the injection of freshwater into the formation likely releases exchangeable B and lithium (Li) from adsorption sites on clay mineral surfaces into produced water.

Barium

Total Ba concentrations in the Petitot River Basin ranged from 15 to 98.9 µg/L; the median was 40.1 µg/L, 25 times lower than the drinking water guideline (1000 µg/L (Health Canada 1990)). Barium is a concern because of its toxicity in drinking water. Produced water in the Marcellus Shale contains elevated concentrations of barium. Similar to B, elevated concentrations of Ba in produced water can be reconciled with leaching directly from fractured rock (Renock et al. 2016).

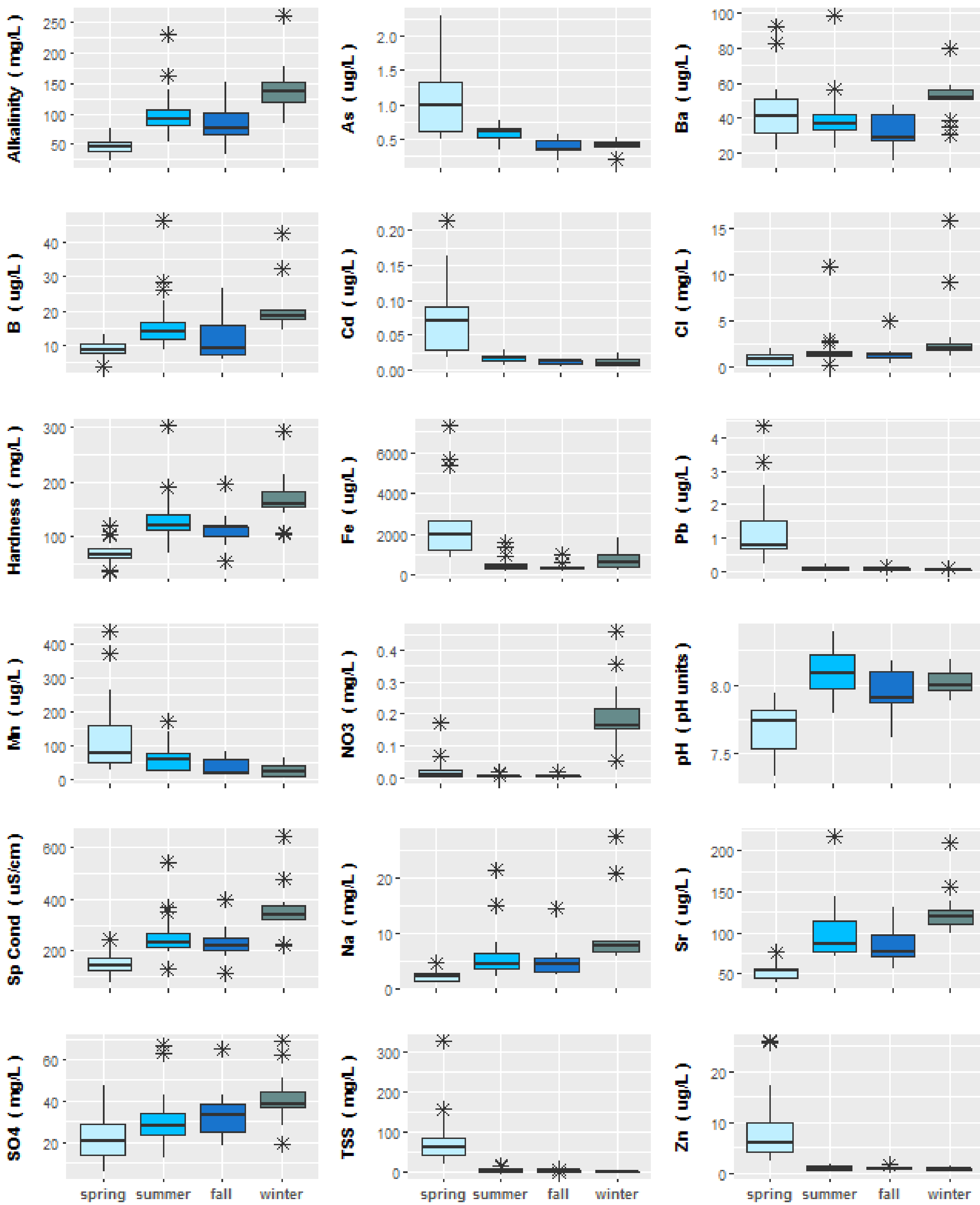
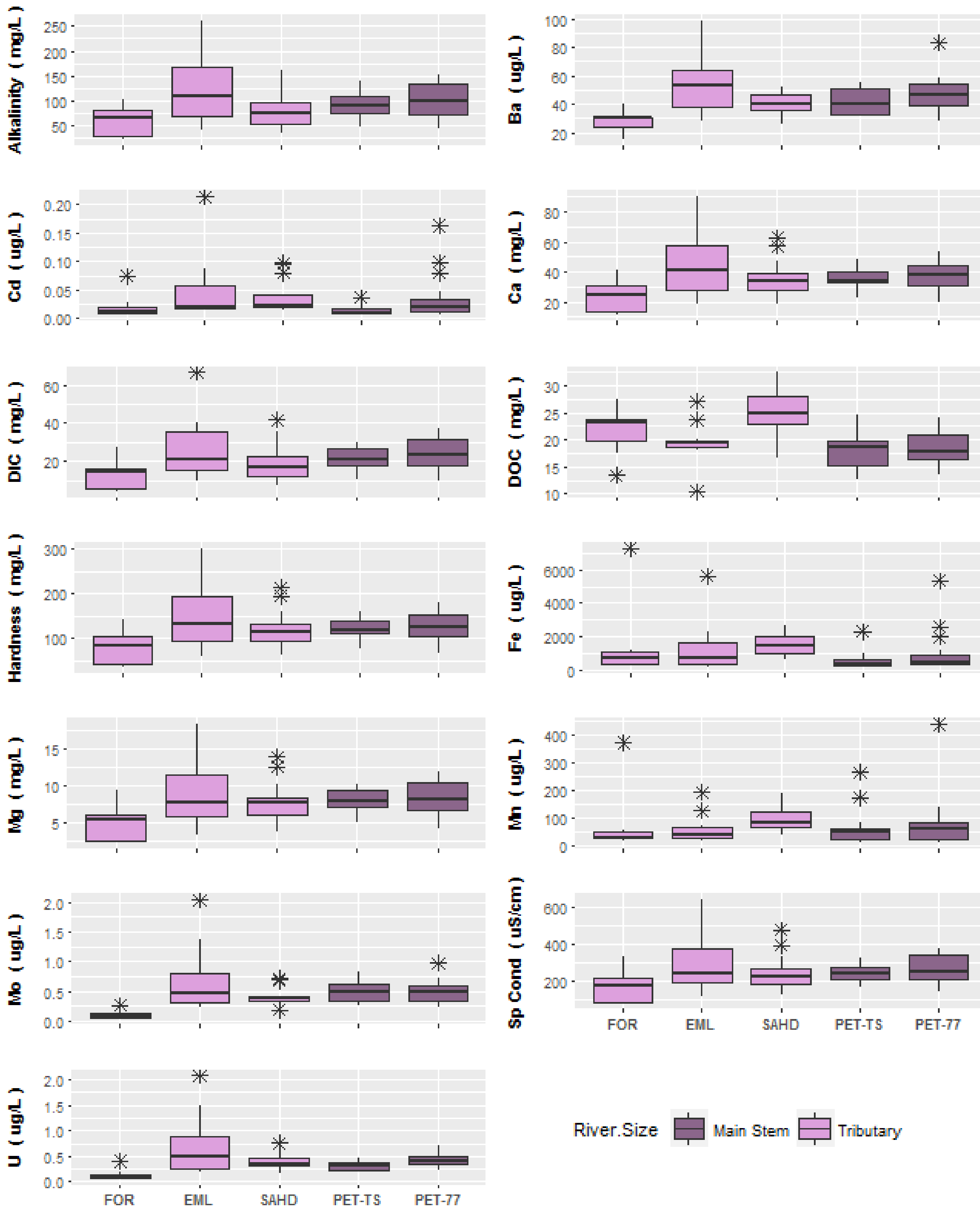


FIGURE A4. *Box plots showing variables with significant seasonal differences within the Petitot River Basin.*



Note: FOR=Fortune Creek, EML=Emile Creek, SAHD=Sahdoanah Creek, PET-TS=Petitot River downstream of Tsea River, PET-77=Petitot River at Highway 77.

FIGURE A5. *Box plots of variables with significant differences between sites within the Petitot River Basin.*

Bromide
Eighty percent of dissolved Br samples from the Petitot River Basin were less than the method detection limit (0.01 mg/L) and similar to concentrations detected in background waters upstream of the UOG waste disposal facility in West Virginia (Akob et al. 2016). There is currently no water quality guideline for bromide. Br is present in organic rich shale and elevated concentrations are found in produced water (Barbot et al. 2013, Lauer et al. 2016).

Calcium, Chloride, Sodium, Total Dissolved Solids
Shale and sandstone produced water have been characterized as Na-Ca-Cl water types and are typically saline (USEPA 2015). High TDS concentrations in produced waters from shale and tight formations identified by the USEPA were typically dominated by high Cl and Na concentrations and with large contributions from monovalent and divalent cations such as Ca (USEPA 2015).

Dissolved Ca concentrations ranged from 11 to 90.3 mg/L and the median concentration was 34 mg/L. Dissolved Mg concentrations ranged from 2.2 to 18.4 mg/L and the median concentration was 7.17 mg/L. There are currently no water quality guidelines for Ca or Mg. Groundwater in the region has been described as bicarbonate of Ca-Mg type with hardness concentrations that range from 250 to 300 mg/L (Rosenneth 1994). High Ca, Mg and hardness concentrations detected are likely from groundwater contribution to surface water.

Dissolved Cl concentrations ranged from <0.1 – 15.9 mg/L; the median was 1.3 mg/L, 460 times less than the aquatic life guideline (600 mg/L, Nagpal et al. (2003)). High Cl concentrations in solution are not easily removed by chemical or biological treatment making produced water expensive to treat (Olmstead et al. 2013). Extreme increases in Cl are seen where spills have occurred. For example, Cl concentrations in Acorn Creek, Kentucky were 8500 mg/L at downstream sites sampled four days after frack fluid was potentially released into waterways and was still 2900 mg/L two weeks later (Papoulias and Velasco 2013).

Dissolved Na concentrations in the Petitot River Basin ranged from 1.1 to 27.6 mg/L with a median of 4.33 mg/L, similar to the median concentration (5.6 mg/L) found in Canadian drinking water (Health Canada 1979). Elevated Na and Cl concentrations were detected in both West Virginia and Bakken spill waters (Barbot et al. 2013, Akob et al. 2016, Lauer et al. 2016).

The median TDS concentration measured in the Petitot River Basin is 170 mg/L, 2.9 times below the guideline (500 mg/L, Health Canada (1991)). Groundwater concentrations measured from the unconfined aquifer in the region range from 300 to 400 mg/L (Rosenneth 1994).

Iron and Manganese
Total Fe concentrations are relatively high in the basin and range from 163 to 7310 µg/L. As discussed in Section A2.1, 39% of samples collected within the Petitot River Basin exceeded the BC guideline for total Fe of 1000 µg/L (Phippen et al. 2008). Many of the exceedances (70%) occurred during high water and are probably associated with high sediment loads during freshet. Other exceedances occurred on tributaries during the winter low flow period and are likely associated with upstream bog and fen areas that dictate regions of groundwater-surface water interactions (Johnson 2010). The median Fe concentration in the basin is 593 µg/L. Iron concentrations up to 5000 µg/L were measured in groundwater from the unconfined aquifer (Rosenneth 1994) suggesting that the elevated concentrations are likely related to groundwater (Figure A6).

Total Mn concentrations measured in the Petitot River Basin ranged from 9.49 to 439 µg/L, with a median value of 49.5 µg/L. Typical Mn concentrations measured in the Cariboo, Omineca and Peace regions range from 2 to 1530 µg/L (Nagpal 2001). A specific guideline value was calculated for each measurement based on hardness (Nagpal 2001) and these were never exceeded.

Iron and manganese oxides within formation solids may be released through the dissolution through acid soluble phases. Under anaerobic conditions microorganisms can mobilize or sequester metals. For example, reducing bacteria mobilises iron and manganese (USEPA 2015). Potential toxic effects from total iron generally occur as either damage to the gills of fish or from decreased visibility in the water which can affect feeding success (Phippen et al. 2008). Manganese is slightly-to-moderately toxic to aquatic organisms.

FIGURE A6. *Iron precipitate observed in a seep on the Petitot River. Photo by Patrick Shaw.*

Strontium

Total Sr concentrations in the basin ranged from 40.1 to 217 µg/L with a median concentration of 79.25 µg/L. There are currently no guidelines for Sr, however, McPherson et al. (2014) proposed a chronic effects benchmark of 10,700 µg/L and the USEPA has set a lifetime health advisory level for Sr at 4000 µg/L (USEPA 2012). The median Sr concentration in the Petitot River was 120 times less than the proposed chronic effects benchmark and 45 times less than the USEPA health advisory level.

Produced water samples from the Marcellus Shale region contains very high concentrations of Ba and Sr. These are likely controlled by the dissolution of Ba and Sr rich minerals such as barite ($BaSO_4$), witherite ($BaCO_3$), celstite ($SrSO_4$) and strontianite ($SrCO_3$) within the shales of the Marcellus Formation (Chapman et al. 2012).

Sulphate

The median concentration of dissolved SO_4 measured in the Petitot River Basin is 30.52 mg/L, 10 times less than the BC guideline for the protection of aquatic life (309 mg/L) for a median hardness concentration of 116 mg/L. The SO_4 guideline is based on water hardness as it has an effect on the toxicity of sulphate to aquatic organisms (Meays and Nordin 2013). In the absence of a maximum guideline the approved 30-day average guideline has been applied to the data. This is also consistent with the mean background level of 26.1 mg/L measured in the Omineca-Peace region (Meays and Nordin 2013).

Sulphate concentrations in produced water vary widely between formations. Sulphate concentration decreases were observed in Marcellus Shale produced water over time due to the slow precipitation of barium sulfate where very little SO_4 is present in the formation. This was confirmed by a decrease in the barium saturation index over 27 days (Barbot et al. 2013).

Comparison to spillwaters

Data documenting impacts to surface water from produced water spills is limited as characterization of produced water is not typically part of the spill response (USEPA 2015). Two case studies have documented the impacts to streams from small spills in North Dakota (Lauer et al. 2016) and downstream of a wastewater injection facility in West Virginia (Akob et al. 2016).

The median Petitot River Basin concentrations have been compared to the concentrations documented in the case studies above. In North Dakota, elevated concentrations of dissolved Na, Br, Cl, selenium (Se), Pb, Vanadium (V) and ammonium (NH_4) were detected in small spill waters relative to average background water concentrations (Lauer et al. 2016). By comparison, median concentrations of dissolved and total variables in the Petitot River were less than background dissolved concentrations measured in North Dakota with the exception of NH_4 which was not analysed (Table A3). In West Virginia, elevated concentrations of dissolved Na, Cl, Ba, Br, Sr, Li, and tota Fe compared to background waters were detected in samples collected downstream of an injection facility that accepts wastewater from 25 production wells in West Virginia. Source water are from varying types of formations including shale gas and coal bed methane (Akob et al. 2016). Again, for variables highlighted, median Petitot River concentrations in total and dissolved form were more similar to concentrations detected upstream of the wastewater injection facility (Table A3).

Grab sample data from the five sites sampled in the Petitot River Basin show no indication of impacts to water quality from produced water. UOG variables identified in produced waters were generally below water quality guidelines, with the exception of Fe. However, median concentrations of Fe were also similar to upstream or background levels when compared with spill waters from both North Dakota and West Virginia.

TABLE A3. *Comparing median concentrations of key UOG variables in the Petitot River Basin to background and spill water in two shale gas resources areas in West Virginia (W.Va) (wastewater injection facility) and North Dakota (ND).*

	PETITOT RIVER BASIN	W.VA.	ND	W. VA.	ND
	(MEDIAN CONCENTRATION)	U/S OF FACILITY	BACKGROUND	D/S OF FACILITY	SPILL WATER
Bromide (mg/L)	<0.01	<0.03	0.73	0.8	5.5
Chloride (mg/L)	1.3	0.88	21	115	5040
Sodium (mg/L)	4.33	6.96	733	56	1841
Barium (µg/L)*	40.1	83		461	
Strontium (µg/L)*	79.25	53.6		830	
Lithium (µg/L)*	5.7	0.00		29.1	
Iron (ug/L)	593	200		8000	
Lead (µg/L)*	0.105		0.2		1.8
Selenium (µg/L)*	0.1		1.1		45
Vanadium (µg/L)*	0.35		3.6		62

Note: D = dissolved, T = total, U/S = upstream, D/S = downstream
* Petitot River metals concentrations are reported as total; ND and W.Va metals concentrations were reported as dissolved.

A2.3 CONTINUOUS WATER QUALITY DATA

Real time water quality networks have been initiated in areas with ongoing UOG drilling, collecting continuous data to track events and determine potential impacts to surface water quality (Hintz and Steffy 2015). Based on the close correlation between TDS and SpCond, the Research Partnership to Secure Energy for America in 2012 considered the use of in-line conductivity loggers allowing operators to measure, separate, and segregate produced waters in real time for recovery and re-use (Hayes and Severin 2012).

In this study, acquisition of continuous water quality data presented challenges resulting in partial data records. Submersible loggers were only accessible during the open water season (May to October) as rivers and streams in the study area were typically frozen throughout the winter months. Installations remained in the rivers during ice freeze up, break up and subsequent freshet periods. Many of the data loggers experienced a combination of issues during 2013-14:

- Loggers were encased in ice over the winter as water levels dropped in Fortune Creek.
- Loggers came out of water at Emile and Fortune Creeks during the summer in 2013.
- Loggers were encased in sediment due to the ONSET factory logger cases having large holes. New cases with smaller holes were designed using slotted PVC pipe and used in future deployments.
- Loggers were lost on the mainstem Petitot River.
- Loggers were not accessible to switch out due to higher than expected water levels and subsequently ran out of memory and stopped taking measurements at the mainstem Petitot sites.
- The natural conductivity levels in the rivers fell outside the calibrated range of the Solinst loggers.

Installations in August 2014 to July 2015 were more reliable. Continuous data were screened and analysed when there were greater than 80% of the expected measurements for a day. Summary statistics, time series and box plots were calculated using data from August 2014 to July 2015. The entire period of record (May 2013-July 2015) excluding the partial days was used when comparing daily minimum water temperature to the applicable guideline.

Specific conductance data from the different conductivity loggers employed were not comparable because natural conductivity levels were out of the calibrated range with one of the loggers. Therefore, there were larger data gaps in the SpCond datasets compared to the water temperature datasets. Completeness tables of the automated results for water temperature and SpCond are in Appendix A.

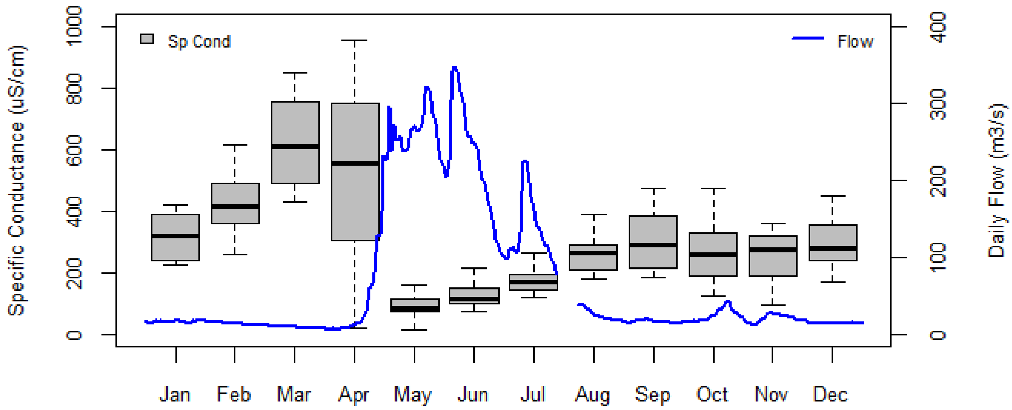


FIGURE A7. *Monthly boxplots of mean specific conductance at five routine monitoring sites plotted with daily mean flow at the Petitot River at Highway 77 hydrometric station for 2014.*

Specific conductance

Monthly boxplots of SpCond from all sites were generated for the 2014 period. Generally, SpCond was inversely related to hydrological patterns (Figure A7) with higher concentrations in the winter and late summer when flow is low with an abrupt decrease during freshet. Higher concentrations during the winter months are likely from increased upstream wetland and groundwater inputs during low flow periods (Saha et al. 2013).

Time series plots of daily mean specific conductance were generated for each site between August 2014 and July 2015; no indication of impacts from produced water were noted (Figure A8). There were higher concentrations and greater variability in tributary streams compared to the Petitot River at Highway 77 and Petitot River downstream of Tsea River sites suggesting that loggers may be more effective monitoring tools in midsize tributary streams than in the mainstem where several flow effects and pollution factors are combined.

Specific conductance in the Petitot River Basin ranged from 70.4 to 668.1 µS/cm (Table A4). Produced waters contain high concentrations of both TDS and major ions, so any release to surface water will quickly influence the specific conductance of the river (Hintz and Steffy 2015). It is unlikely that a significant release of effluent impacted any of the sites monitored in the Petitot River Basin between August 2014 and July 2015. In other regions, spill events related to produced waters typically result in SpCond values at least an order of magnitude higher than those observed in the Petitot. For example, the release of fracking fluids into Acorn Creek, Kentucky, resulted from fracking effluent overflowing the retention pits directly into the creek. The conductivity increased from 200 to 35,000 µS/cm and the effects were detected as far as 3 km downstream, where conductivity was 1265 µS/cm one month later (Papoulias and Velasco 2013).

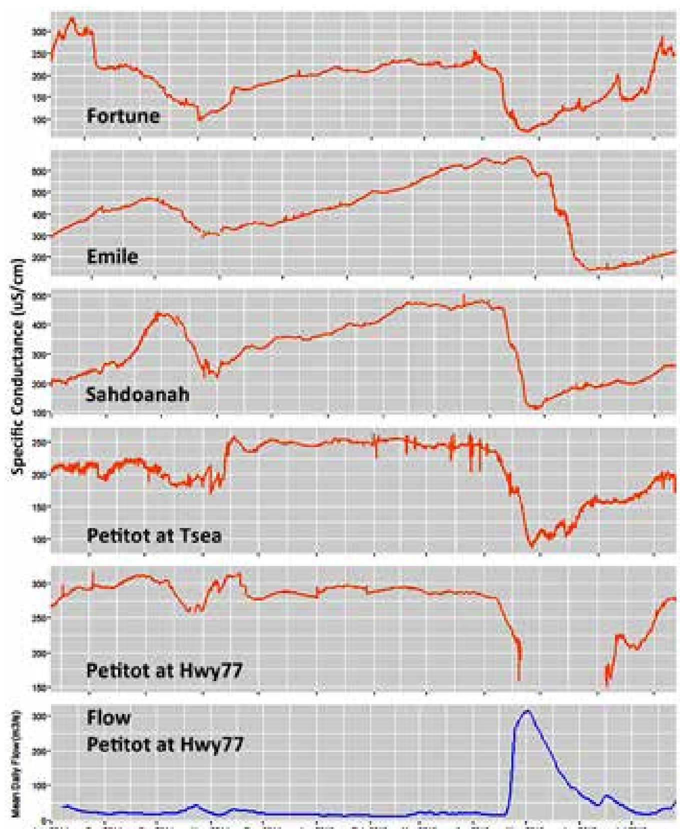


FIGURE A8. *Time series plots of specific conductance at five routine monitoring sites in the Petitot River Basin and flow at the Petitot River at Highway 77 hydrometric station from August 2014 to July 2015. Specific conductance scales have been adjusted to the data.*

TABLE A4. *Summary statistics for specific conductance by site from August 2014 to July 2015.*

SITE	% COMPLETENESS	MIN	MEDIAN	MEAN	MAX	STDEV
Emile Creek	81.9	136.20	418.20	412.66	668.10	146.35
Fortune Creek	91.0	70.40	198.80	187.57	332.30	54.65
Petitot River at Highway 77	91.8	149.50	286.90	279.18	316.00	27.58
Petitot River below Tsea River	N/A	N/A	N/A	N/A	N/A	N/A
Sahdoanah Creek	75.6	109.80	343.90	323.15	501.70	109.70
Petitot River Basin	92.1	70.40	285.6	297.07	668.10	126.55

Note: % completeness is based on the percentage of complete days. A complete day is defined as greater than 80% of the expected daily record.

Water temperature

Water temperature in the Petitot River Basin typically varies with both the predominant run-off phases and climate (Section 4). Run-off phases defined for the Horn River Basin area are: snowmelt-based run off from March to early May; rainfall runoff from May to mid-October; and winter low flow from mid-October to March (Johnson 2010). Time series plots of daily mean water temperature were generated at each site from May 2013 to July 2015, the entire period of record (Figure A9).

At each site, summary statistics for water temperature were calculated for the most complete subset of data, from August 2014 to July 2015 (Table A5). The range of water temperature values in the Petitot River Basin show that from November to March water temperature is close to 0°C. After ice break up, water temperature increases in May to a maximum value of 26.1°C in July (Figure A9). It then decreases steadily from August until freeze up in November (Figure A9). The month of May was the most variable, suggesting that water temperature in the basin increases rapidly as snowmelt based runoff changes to rainfall runoff. Generally all the sites in the basin displayed similar patterns in monthly water temperature.

The total number of days in each month where the minimum daily temperature exceeded the BC guideline (19°C) was calculated for each site (Appendix A). The BC guideline was generally exceeded May through August, with the highest number of days exceeding the guideline in July for all sites. Sahdoanah and Fortune Creek have fewer days exceeding the guideline than Emile and the mainstem Petitot River sites.

TABLE A5. *Summary statistics of automated water temperature by site from August 2014 to July 2015.*

SITE	% COMPLETENESS	MIN	MEDIAN	MEAN	MAX	STDEV.	NO. OF DAYS EXCEEDING TEMPERATURE GUIDELINE
Fortune Creek	94.8	0.24	0.39	5.44	21.95	6.60	74
Emile Creek	94	0.06	0.22	5.9	24.00	7.49	123
Sahdoanah Creek	91.8	0.02	0.11	5.31	23.38	6.88	74
Petitot River below Tsea River	91.8	-0.4	-0.3	5.75	26.10	7.93	94
Petitot River at Highway 77	91.8	-0.06	0.1	6.22	24.84	8.09	111
Petitot River Basin	95.1	-0.4	0.35	5.77	26.10	7.42	N/A

Note: % completeness is based on the percentage of complete days. A complete day is defined as greater than 80% of the expected daily record.

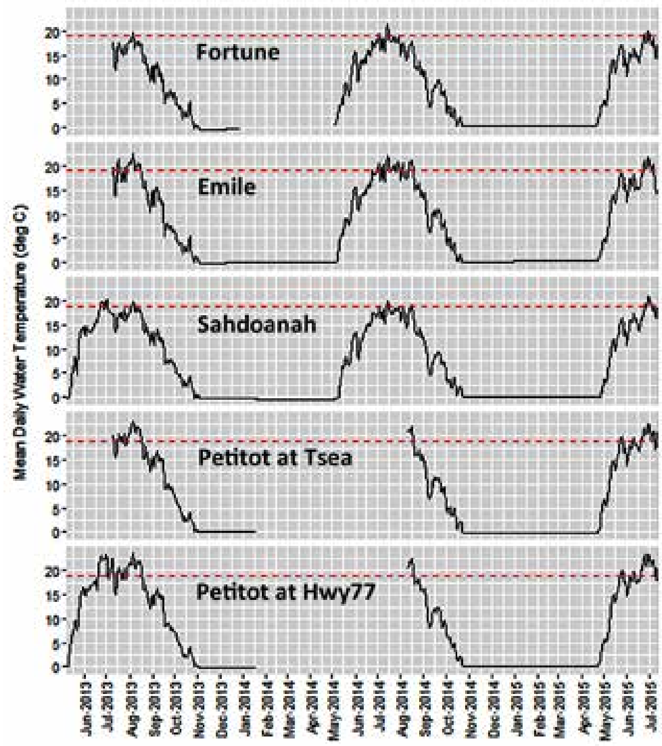


FIGURE A9. *Time series plots of mean daily water temperature by site from May 2013 to July 2015. The BC guideline for the protection of aquatic life (19°C) is shown in red.*

A3. CONCLUSIONS AND RECOMMENDATIONS

Routine monitoring results did not detect any large scale impacts from UOG activities in the Petitot River Basin.

- Water quality throughout the year is dominated by spring freshet in May and upstream wetland areas that control groundwater-surface water interactions during winter base and summer low flows (Johnson 2010). Cadmium and Fe exceeded guidelines in the spring during freshet and were likely related to high sediment loads in the rivers and contributions from wetlands and groundwater. Water temperature exceeded the water quality guideline (19°C) in May, June, July and August with the highest number of warm days in July.
- A long-term water quality station at the Petitot River at Highway 77 was incorporated into the federal-provincial monitoring network in 2015.
- Fortune Creek had the smallest drainage area, the least amount of UOG activity in the basin and lower concentrations than the other sites. Differences in physical water quality variables are likely due to basin size as smaller streams and rivers are more responsive to rain events. Differences in As, Ba and U may reflect minor impacts from the management of drill cuttings and further investigation is required.
- When compared with documented impacts to streams by spills or releases of produced water in the US, Petitot River Basin concentrations were similar to or less than background concentrations. Continuous water quality data indicates no evidence of produced water spills between August 2014 – July 2015.
- Submersible conductivity loggers can be an effective way to monitor impacts to streams from spills or accidental releases in the area. Loggers may be more effective monitoring tools in midsize tributary streams than in larger rivers.

PART B
SYNOPTIC WATER QUALITY MONITORING

B1. METHODS

B1.1 STUDY DESIGN AND SITE SELECTION

Design of the synoptic component of the program was predicated on an expectation that measurable UOG related contaminants in surface waters could result from at least three potential routes. These could be: 1) direct entry through spills during transport or storage of chemicals or produced waters, 2) leaking storage facilities, such as flowback or produced water holding ponds, or, 3) groundwater contamination resulting from leakage along production well boreholes (possibly from leaking casings) with subsequent transmission to surface waters. The first route would be expected to be transient while others could potentially result in a more chronic source and could be detectable over a longer time period. Since the synoptic program, as with most water chemistry sampling, relied on infrequent grab sampling, it would be quite possible that spills would go undetected.

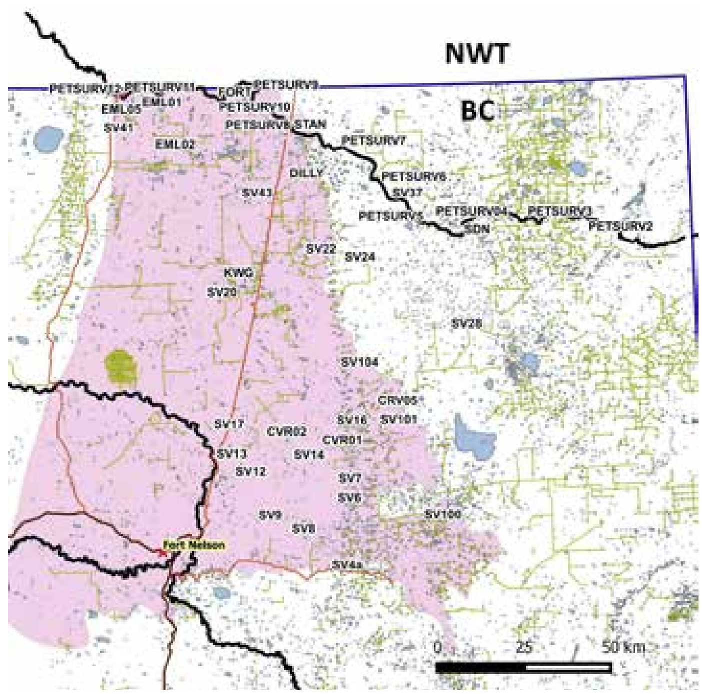


FIGURE B1. *Study area north of Fort Nelson showing the complete suite of sampling locations. The shaded inset shows the boundaries of the Horn River Basin shale gas play.*

Sample sites in the initial stages of the program were selected based on proximity to gas extraction or production facilities. Four sites near gas production facilities and one additional site on Fortune Creek with a lower level of industrial activity for comparison were sampled in May 2012 (CRV05, EML01, FORT, SDN, KWG in Figure B1).

Subsequent sampling was at sites determined by GIS as described in Section 5. Using the basin delineations and BCOCG data layers, a suite of sites were selected to represent a range of levels of industrial activity and potential contamination.

In addition to water quality sampling locations at the drainage outlets of microbasins, a series of samples were collected along the mainstem Petitot River at 20 river kilometre intervals from the Alberta border to the Highway 77 bridge over the Petitot River (Figure B2). The intent of this longitudinal sampling was to capture potential "step-changes" in water chemistry as the river flows through the northeast BC gas production area.

FIGURE B2. *Petitot River watershed showing location of mainstem longitudinal (PETSURV) water quality sampling locations.*

B1.2 SAMPLE COLLECTION

Water grab samples were collected in 2013 and in 2014 as near as possible to peak freshet (May) and at low water (August) via helicopter access (Figure B3). Samples were collected by wading and bottles were filled by hand and analysed for the standard suite of physical/chemical variables and total metals. Field measurements including pH, SpCond, conductivity, and water temperature were recorded by in situ multi-probe. Samples were kept cool and shipped to analytical laboratories as soon as possible after collection.

Information relating to the chemical composition of produced waters for UOG activity around the Horn River Basin was not available when the preliminary surveillance survey was initiated in 2012 (Alan Chapman, BCOGC, *pers. Comm. Aug 2012*). A suite of water quality variables to be measured was based on key indicator variables in published studies from other areas where hydraulic fracturing was occurring (Haluszczak et al. 2013, Olmstead et al. 2013, Spellman 2013, Vidic et al. 2013, Abualfaraj et al. 2014). These published studies have particularly implicated Ba, B, Sr, SO_4 and Cl as key indicator components of flowback return waters and were of particular interest in the present work. The complete set of physical/chemical analytes with accompanying detection limits and analytical method are presented in Appendix B (Tables B1-B4). Chemical analyses were conducted by ECCC's PYLET, North Vancouver, BC. Total metals were measured at the NLET, Burlington, ON by Inductively-coupled Plasma Mass Spectrometry (ICP-MS) after in-bottle digestion.

In addition to core physical chemical variables an array of trace organic chemicals were also measured in the initial stages of the program in 2012 and opportunistically as resources permitted. The 2012 analyte spectrum was drawn from the list of organic chemical components used in hydraulic fracturing fluids, as identified in material from the BCOGC (www.bcogc.ca).

FIGURE B3. *Water sampling on the Petitot River, May 2014. Photo by Patrick Shaw.*

In addition, organic compounds otherwise associated with drilling and oil/gas extraction – PAHs and naphthenic acids (NAs) – were also measured.

Passive samplers, Polar Organic Chemical Integrative Samplers (POCIS; Alvarez (2010)) were deployed in May-June 2012 at six locations in the study area. These devices accumulate and concentrate polar contaminants from surrounding water, and are particularly useful where concentrations of target analytes are below typical analytical detection limits and may have time-varying concentrations. The POCIS consist of a resin enclosed within a membrane and preferentially accumulate polar organic compounds from the surrounding water over the period of exposure. In this application the units were deployed in May 2012 and retrieved in June 2012. These were subsequently extracted and analyzed for NAs by Axys Analytical Services, Sidney, BC using a method described in Woudneh et al. (2013). While POCIS can be used to estimate in-stream concentrations of some particular classes of contaminants, only a presence or absence is currently possible for NAs. Since POCIS deployments for NAs provided only qualitative data, additional grab samples were collected in January 2013 and August 2014 to obtain estimates of instream NA concentrations. Samples were collected into cleaned 1L amber glass bottles and submitted to Axys Analytical Services, Sidney, BC for analysis using the method described in Woudneh et al. (2013).

Grab samples were collected in May 2012 and analyzed for a suite of chemicals used in fracking fluids: volatile organic compounds (VOCs) by ECCC's PYLET, North Vancouver, BC, PAHs by Axys Analytical Services, Sidney, BC. Samples for PAH analyses were collected into 1L pre-cleaned amber glass bottles and preserved with sodium azide. The complete set of chemical analyses with analytical methods and accompanying detection limits are presented in Appendix B.

B1.3 DATA ANALYSIS

Data were screened for outliers and errors, and summary statistics were calculated for variables where greater than 90% values exceeded the method detection limit (MDL). Where necessary, non-detect values were replaced with a random value between 0 and the MDL. Relationships between water quality variables were explored using bivariate plots and Spearman Rank Correlations and samples collected at a single site over several years were also compared using bivariate plots.

Relationships between chemical variables for low and high water sampling periods were explored using principal component analysis (PCA). Data were centred and standardized prior to PCA calculations on a correlation matrix in SYSTAT 13 version 13.1 (SYSTAT Software, 2009a). From this analysis, a subset of chemical variables whose concentrations were least affected by flow-related suspended solids was selected for further examination.

Data display and statistical analyses were conducted using SigmaPlot 11 version 11.2 (SYSTAT Software 2009b), SYSTAT 13 version 13.1 (SYSTAT 2009a) and CANOCO 4.5 (Ter Braak and Šmilauer 2002).

B2. RESULTS AND DISCUSSION

B2.1 SAMPLING PERIODS

Sampling was conducted to capture the high and low flow period in each of 2013 and 2014 (Figure B4a and Figure B4b). Although flows for much of 2013 were overall lower than in 2014, 2013 saw an abbreviated freshet period (Figure B5). Complete coverage of all sites during each visit was not possible due to weather, flow-related access and time constraints, while other sites were only sampled during the initial work in 2012 (Table B1).

FIGURE B4. *Two images of the Petitot River showing the water levels at A) high (May) and B) low (August) flow periods. Photos by Pat Shaw.*

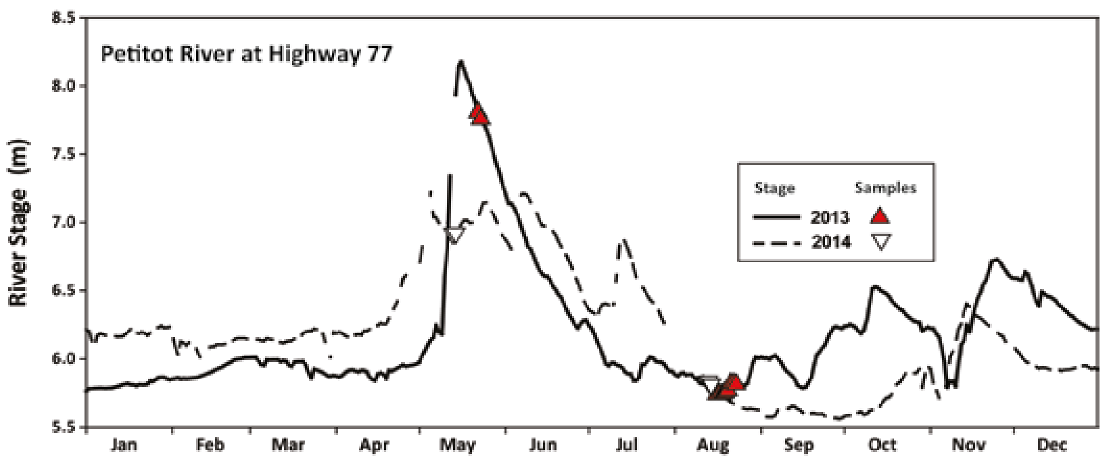


FIGURE B5. *Hydrograph of the Petitot River at Highway 77 during 2013 and 2014 showing low and high water sampling periods. Data from Water Survey of Canada.*

TABLE B1. *Sampling frequency at surveillance sites in the study area from 2012-2014. PETSURV sites are longitudinal sites on the mainstem Petitot River (see B1.1). Symbols: * = routine water chemistry, + = POCIS Deployment for Naphthenic Acids, X = grab sample for Naphthenic Acids, P = grab sample for PAHs.*

		2012		2013		2014	
SAMPLE SITE	ENVIRODAT CODE	MAY	AUG	MAY	AUG	MAY	AUG
CVR01	BC10CE0004		*		P		
CVR02	BC10CE0003			*			
CRV05	BC10CE0007	+ P	*	*	* P	*	* P X
DILLY	BC10DA0024		*	*	*	*	
EML01	BC10DA0018	+ P	*	*	* P		* P X
EML02	BC10DA0020		*			*	*
EML05	BC10DA0019			*	*	*	
FORT	BC10DA0003	+ P	*	*	* P	*	* P X
KWG	BC10CF0006	P		*	*		
STAN	BC10DA0023		*	*		*	*
SV37	BC10DA0027		*			*	*
SDN	BC10DA0036	+ P		*	* P	*	* P X
SV4a	BC10CE0016		*				
SV6	BC10CE0011			*			
SV7	BC10CE0010				*		
SV8	BC10CE0015			*			
SV9	BC10CE0014			*	* P		
SV12	BC10CE0013				*		*
SV13	BC10CE0001			*	* P		* P X
SV14	BC10CE0002		*	*	P	*	* P X
SV16	BC10CE0005				*		
SV17	BC10CF0002			*	* P	*	* P X
SV20	BC10CF0005				*		
SV22	BC10DA0032		*	*		*	
SV24	BC10DA0031				*		
SV28	BC10DA0034					*	*
SV41	BC10DA0017		*		*	*	* P X
SV43	BC10DA0025				*		
SV100	BC10CE0012		*				
SV101	BC10CE0008		*		*		
SV104	BC10CE0009		*				
PETSURV2	BC10DA0014			*		*	* P X
PETSURV4	BC10DA0012			*	*	*	*
PETSURV3	BC10DA0013			*	*	*	*
PETSURV5	BC10DA0004		*	*	P	*	*
PETSURV6	BC10DA0011			*		*	*
PETSURV7	BC10DA0010			*	*	*	* P X
PETSURV8	BC10DA0008		*		*	*	*
PETSURV9	BC10DA0007			*		*	*
PETSURV10	BC10DA0006			*	*	*	*
PETSURV11	BC10DA0005			*		*	*
PETSURV12	BC10DA0002	+ P		*	*	*	* P X

B2.2 INORGANIC VARIABLES

Spatial sampling

A statistical summary of select water chemistry variables for the high and low water sampling periods in 2013 and 2014 is presented in Table B2. Non-detects or values below MDL were infrequent and excluded from calculation of summary statistics.

TABLE B2. *Summary high and low water chemistry for samples collected during 2013/2014. Standard water quality variables and hydraulic fracturing indicator variables are included. Full variable list and summary statistics in Appendix B. *N=47 for all high-water variables except dissolved boron (26) and dissolved strontium (46); +N=46 for all high-water variables except dissolved boron (41)*

		HIGH WATER (N=47*)					LOW WATER (N=46+)				
	UNITS	MIN	MAX	MEAN	MEDIAN	SE	MIN	MAX	MEAN	MEDIAN	SE
Total Alkalinity	$mgCaCO_3/L$	12.3	75.4	41.5	43.0	0.29	35.9	181	109.8	106.0	0.63
pH	-	6.95	7.96	7.69	7.77	0.00	7.47	8.41	8.14	8.21	0.00
Dissolved Inorganic Carbon	mg/L	2.6	16.6	9.1	9.50	0.07	6.4	42	25.9	24.8	0.16
Dissolved Organic Carbon	mg/L	17.5	29.4	23.1	23.1	0.05	15.2	47.7	29.2	28.0	0.18
Total Suspended Solids	mg/L	5	283	53.5	32.0	1.17	1	95	8.9	5.0	0.34
Total Nitrogen	mg/L	0.45	0.89	0.64	0.64	0.00	0.48	1.14	0.77	0.71	0.00
Specific Conductance	µS/cm	60	327	150	151	1.29	112	389	251	238	1.32
Hardness	$mgCaCO_3/L$	30	164	72	70	0.59	68	214	136	128	0.75
Dissolved Chloride	mg/L	0.05	0.60	0.2	0.2	0.00	0.05	0.9	0.4	0.3	0.01
Dissolved Sulphate	mg/L	4.5	78	26.4	24.7	0.39	0.6	59	25.3	24.7	0.28
Total Barium	µg/L	15.8	115	39.2	33.8	0.42	21.7	55.7	38.7	38.3	0.15
Total Boron	µg/L	4.4	16.8	9.3	9.3	0.05	5.8	29.8	14.0	13.5	0.10
Total Strontium	µg/L	20.7	125	53.4	53.8	0.47	49.7	170	99.5	88.1	0.67

Water chemistry in the study area likely reflects weathering of the underlying carbonate sedimentary bedrock. Surface waters were hard to moderately hard and well buffered with neutral to alkaline pH, consistent with monitoring results found in Part A (Figure B6). The landscape is dominated by wetlands and marshes, reflected in generally highly coloured waters with high DOC, at some sites >45 mg/L. Br, which has been reported in high concentrations in produced water (Spellman 2013, Hintz and Steffy 2015) was less than the method detection limit (0.02 mg/L) in almost all samples.

High freshet flows during snowmelt cause mobilization of bed sediments, resulting in increases in total suspended solids and many associated trace metals. As well, there are dilution-related reductions in the concentration of many dissolved ions and related variables such as conductivity (Figure B6; Figure B7). Conversely at low flow, dissolved components such as dissolved ions, some soluble metals, and DOC were elevated likely due to a relatively higher contribution of groundwater to the surface flows (Figure B6; Figure B7; Appendix B). Concentrations of some UOG indicator variables including dissolved base cations (Na) and anions (SO_4, Cl), and metals such as Sr, Ba, and B were largely unrelated to suspended solids (Table B2; Figure B7).

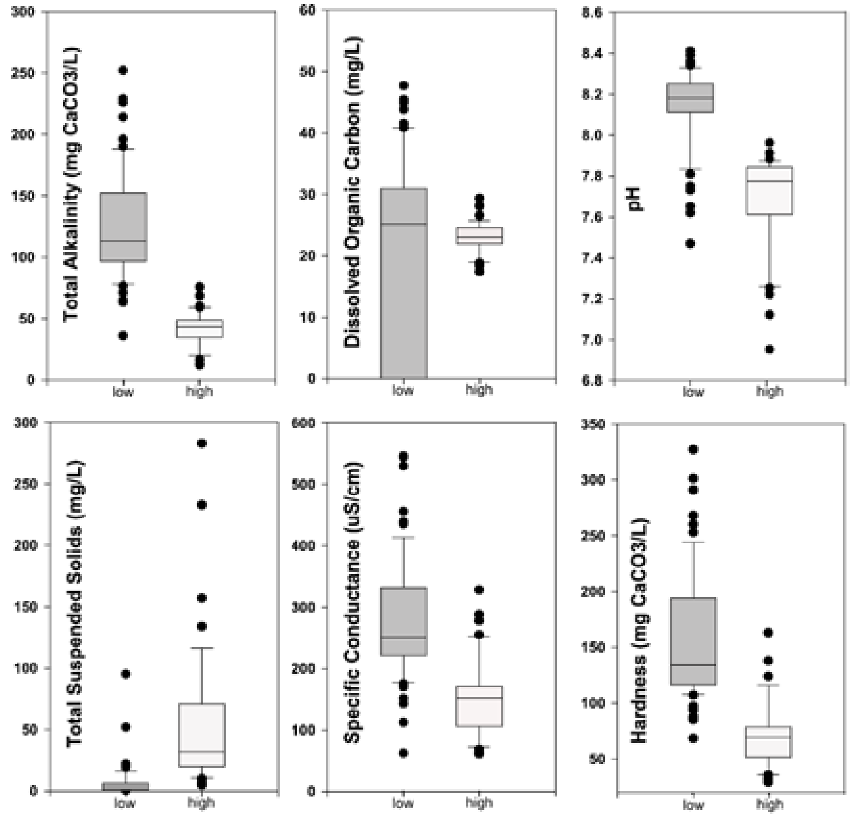


FIGURE B6. *Summary box and whisker plots showing general water quality variables during low and high water at study sites in 2013-2014.*

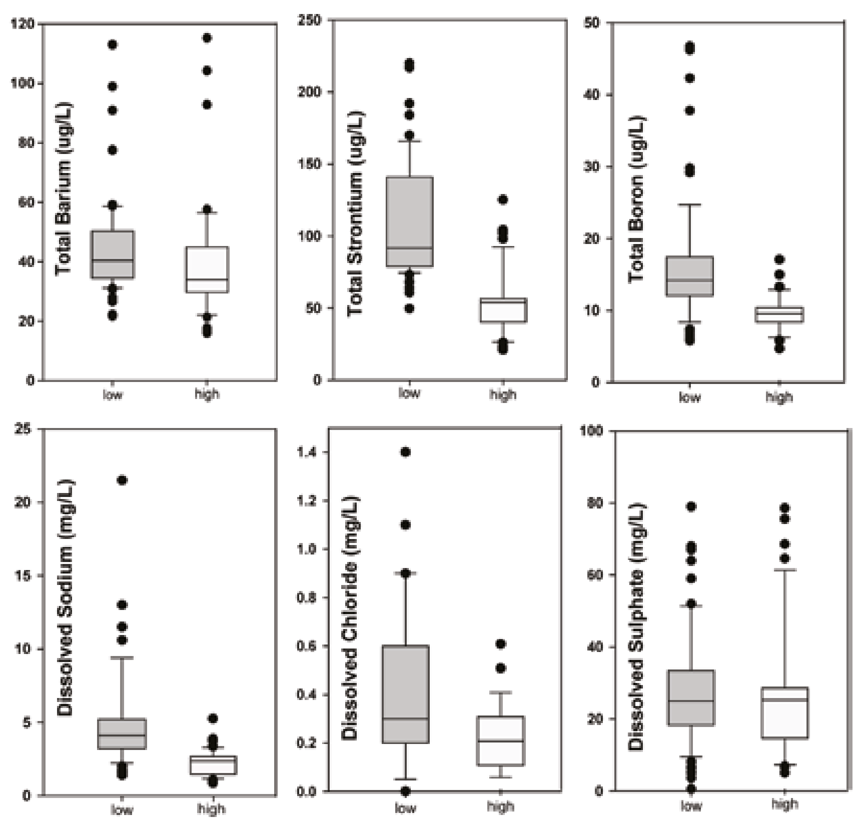


FIGURE B7. *Summary box and whisker plots showing key indicator variables of produced waters at the study sites in 2013-2014.*

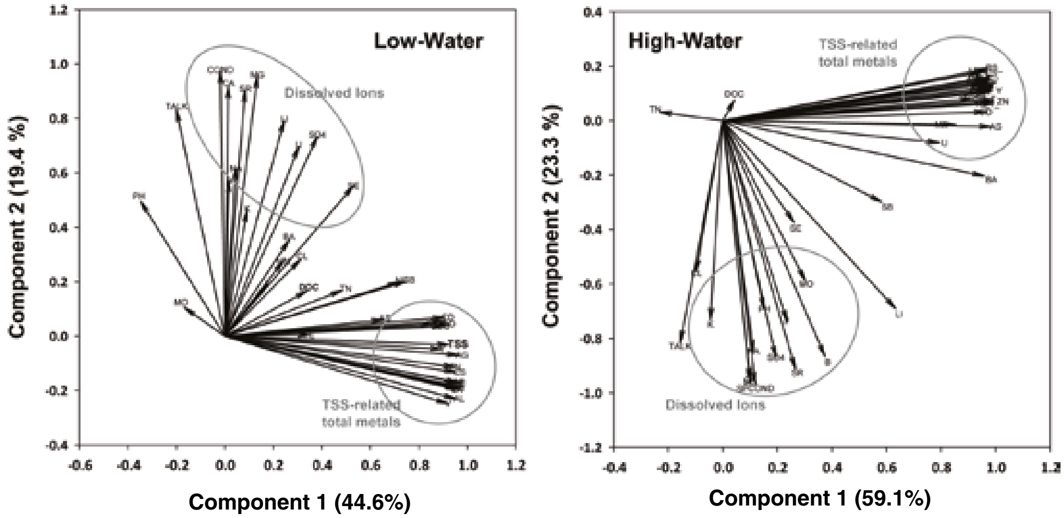


FIGURE B8. *PCA component loadings for all surveillance water chemistry variables at low and high water conditions. Percentages represent the variance attributed to each respective axis.*

Total trace metal concentrations were largely controlled by levels of TSS. Principal component analysis of both the low and high water chemistry data highlighted the association between TSS and metals, and a strong contrast with dissolved variables (Figure B8).

A biplot of sample sites with a reduced variable set showed very similar chemistries at low flows, with some separation of individual sites largely based on differences in TSS, DOC, or Sr (Figure B9). In high flow conditions, the distinctions were more evident with weak contrast on PC1 between sites in the northern and southern (specifically SV14, SV9, SV17) parts of the study area (Figure B9). As well, some sites in 2013 (EML01 and STAN) are far afield in the high water plot, reflecting the effect of the high freshet flows and the high TSS.

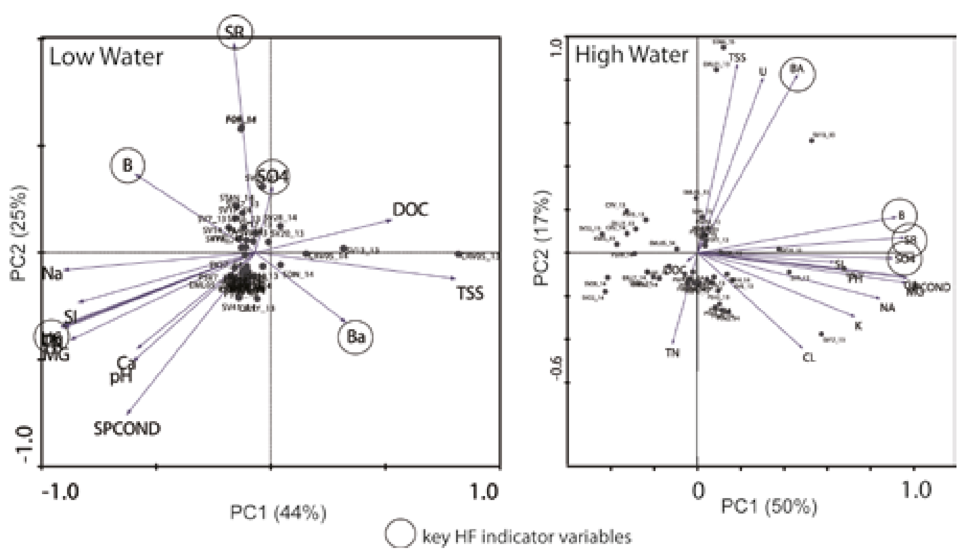


FIGURE B9. *Biplots showing the synoptic sampling sites and water chemistry for the reduced chemistry dataset at low and high flow periods. Site designations show the site and year of sampling.*

Piper Plots of the complete dataset demonstrate the uniform pattern in dissolved cation and anion chemistry both throughout the study area and between high and low flow periods (Figure B10). Low flow conditions with low SO_4, Cl and Na suggest base-flow conditions dominated by shallow groundwater recharge. High flow chemistry is similar, although with an increase in SO_4 relative to bicarbonate (HCO_3) consistent with dilution from freshet runoff. The sole exception is a single high flow sample from SV17 in 2013, a site near the Fort Nelson River which showed elevated SO_4 (75 mg/L) and correspondingly elevated Na and Sr. This single sample falls in a region of the plot where elevated SO_4 and Cl could be an indication of possible brine contamination (Figure B10).

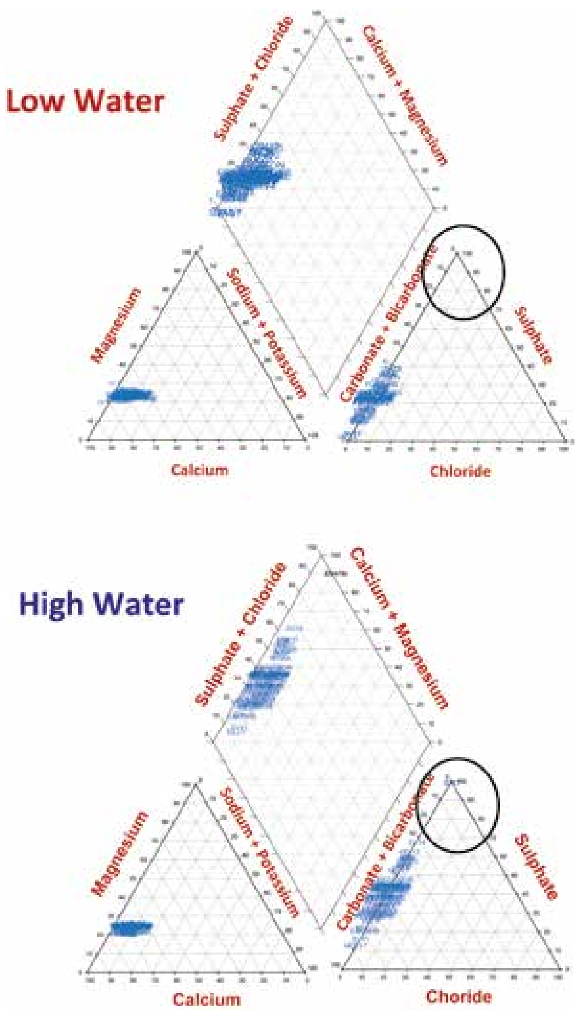


FIGURE B10. *Piper Plots showing patterns in ion chemistry at all study sites for 2013 and 2014 at low (August) and high (May) water periods. The overlaid circle indicates the expected plotting region of chemistry indicative of brine contamination.*

Longitudinal sampling on the Petitot River
Downstream trends in key fracking water indicator variables are shown in Figure B11. Low flow sampling on the Petitot River showed steady downstream increases (east to west) of a number of dissolved variables including Sr and Ba, which could be resulting from a combination of both the increasing groundwater contributions to the base flow and evaporative concentration over the 100 kilometre distance of river travel. The river at this point in the hydrologic cycle is both shallow and warm (mid-day temperature >20°C); conditions which would be highly conducive to evaporative loss. Stepchanges in constituent concentrations were not evident, so point-source contamination to the main river is unlikely or obscured by dilution in the mainstem Petitot.

Constituent concentrations were, with a few exceptions, lowest in the high flow freshet period. Depression in concentrations at some sites and years are clearly evident (PetSurv5 in 2013 and PetSurv9 in 2014), and reflect dilution from tributaries. Sampling was by wading from a helicopter landing point on the river bank, the precise location of which depended upon water level. As a consequence, water collections at high water were affected by upstream tributaries.

Concentration of most constituents track closely between years. The particular exception is that of high water Ba samples, which are 15 – 20 µg/L (50 – 70%) higher in 2013 downstream of PetSurv5. The immediate upstream tributary is the Tsea River, which could potentially have been a source but would need further investigation to confirm.

Temporal sampling
Year on year concentrations of the key fracking indicator variables are shown in Figures B12 and B13. For the most part, constituent concentrations were similar between years for each flow regime and it would be possible to attribute divergence to differences in hydrologic conditions. For example, constituent concentrations in low flow samples collected in 2013 tended to be somewhat higher than those collected in 2014 because of drier conditions in that year. Of note is that more southerly sites (SV12, SV13, SV17) tend to have somewhat higher concentrations of dissolved constituents, related perhaps to watershed geology.

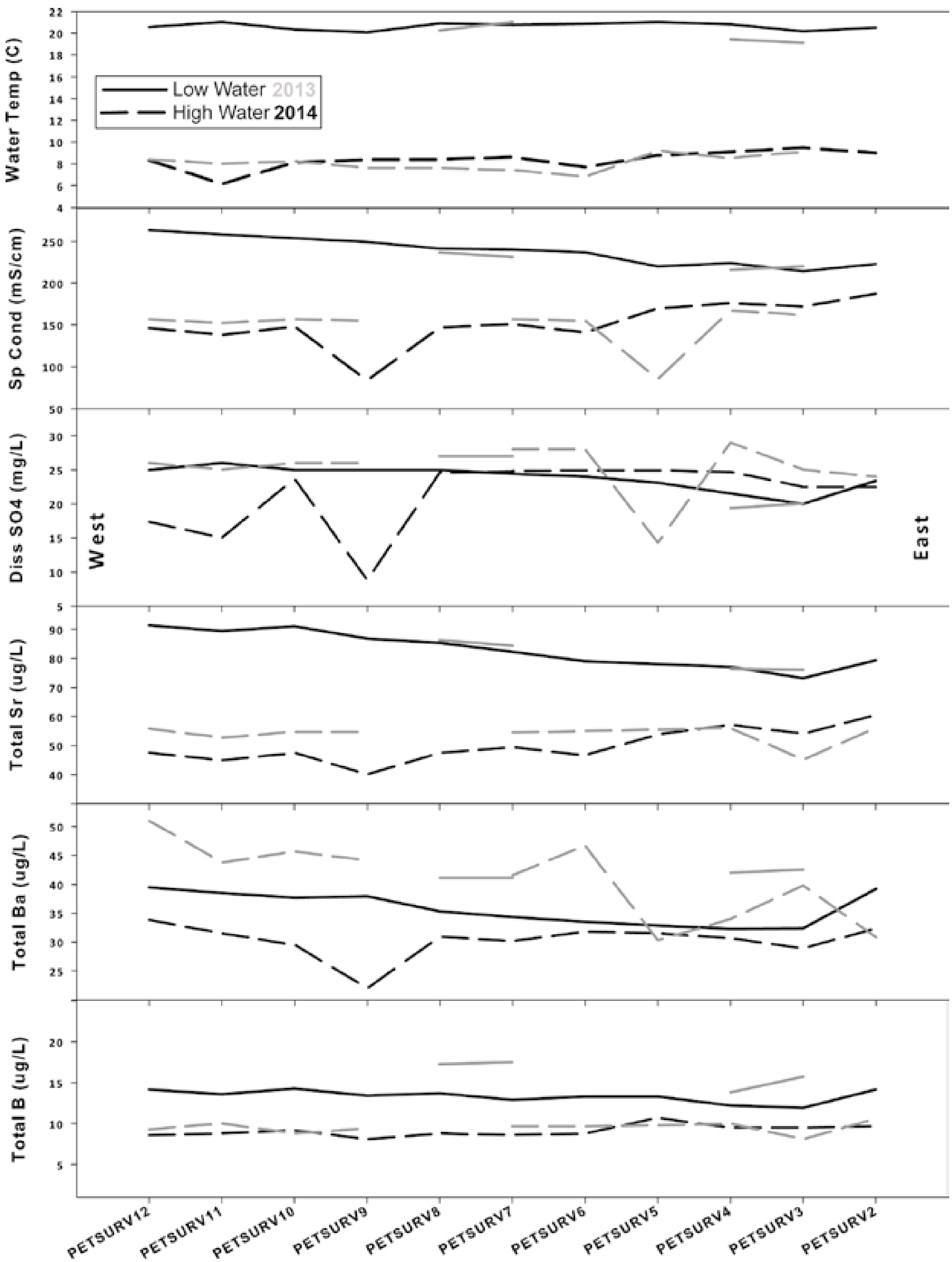


FIGURE B11. *Water chemistry for select variables in the Petitot River mainstem, 2013-2014 longitudinal samples. Site PetSurv2 is located to the east near the Alberta/BC border and PetSurv12 is at the Highway 77 crossing near the confluence with the Liard River. Low water samples are solid lines, high water samples are dashed; samples from 2013 are shown in Grey, 2014 in Black.*

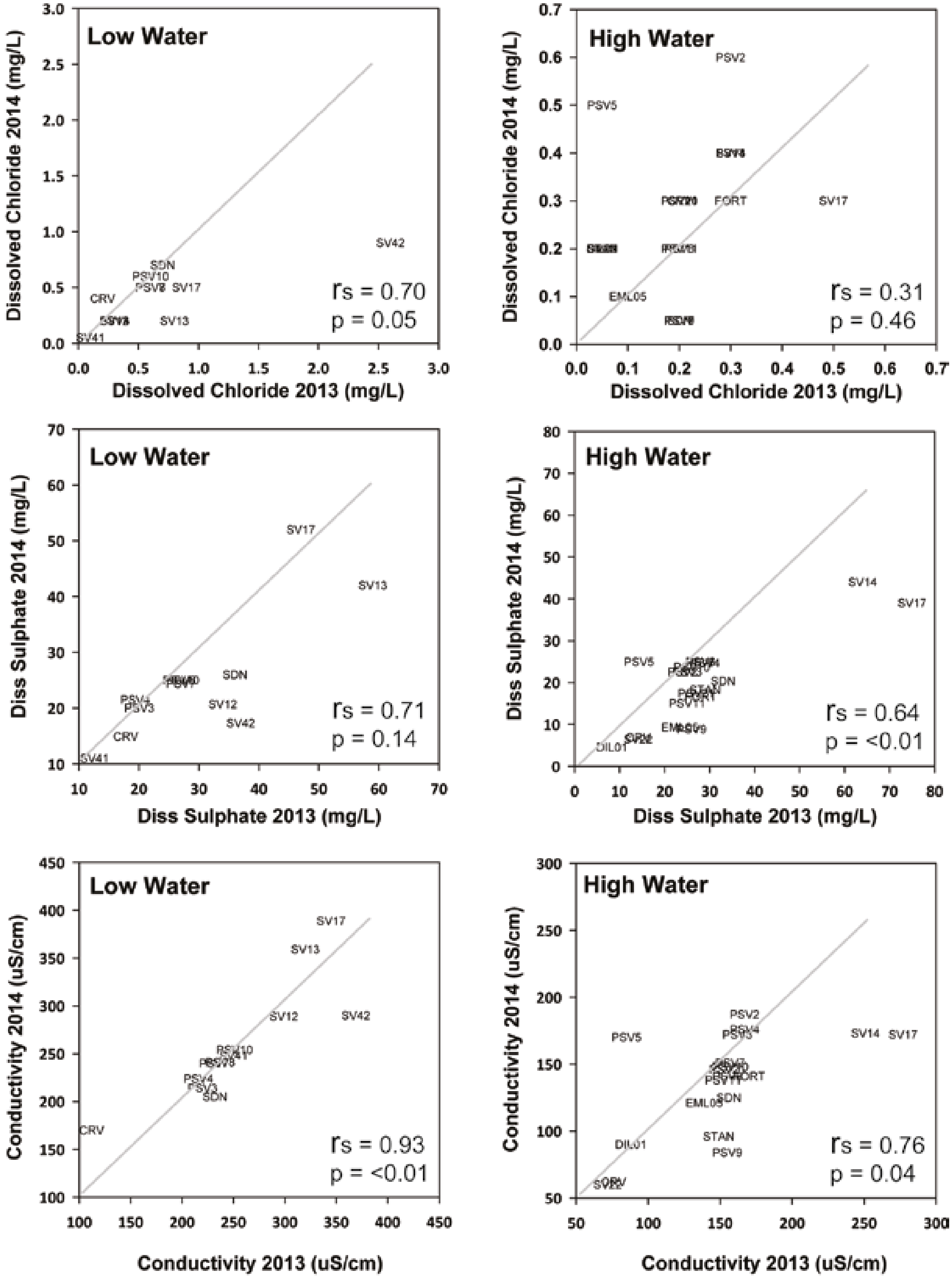


FIGURE B12. *Relationships between concentrations of select water quality variables between 2013 and 2014 at high and low water periods.*

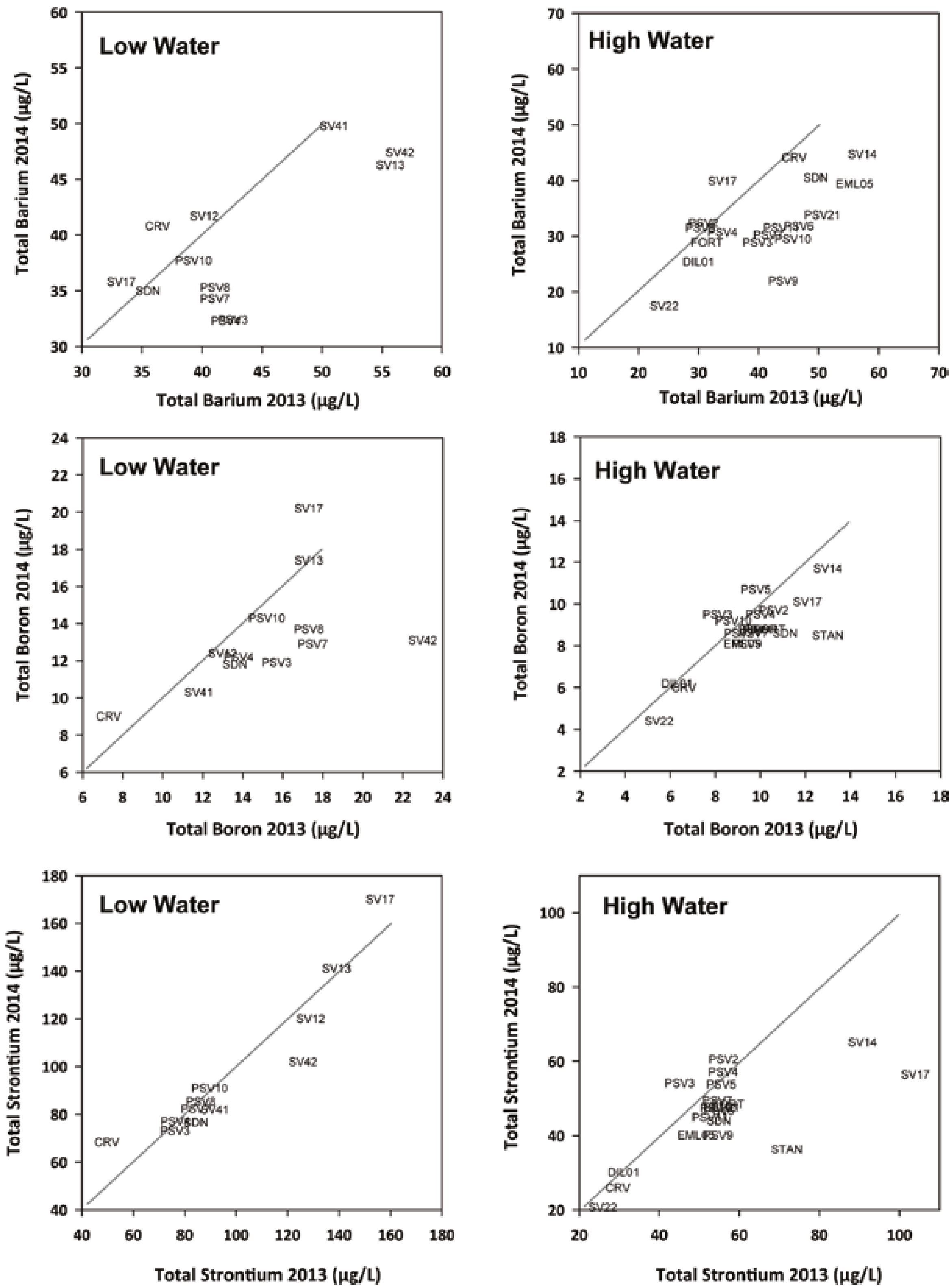


FIGURE B13. *Relationships between concentrations of select UOG indicator water quality variables between 2013 and 2014 at high and low water periods.*

B2.3 ORGANIC VARIABLES

Organic compounds associated with UOG activity
A suite of alcohols and acids used in hydraulic fracturing fluids and set of 48 VOCs were analyzed in samples from six sites in May 2012 (Appendix Tables B2-B4). Trace levels of toluene (0.14 – 0.17 µg/L: DL=0.05 µg/L) and benzene (0.1 µg/L: DL=0.01 µg/L) were measured at all six sites. No other variables were detected.

Diesel range (DRO) and residual range organics (RRO) were measured in May 2012 and in through-ice samples collected in February 2014. The analytical method (EPA Method 8015c) determines the concentration of general classes of organic compounds with boiling points corresponding to diesel (chain length $C_{10} – C_{28}$) and residual range organics ($C_{25} – C_{36}$). While detections may correspond to petroleum contamination, these can be due to non-petroleum compounds including a range of biogenic and synthetic compounds including phthalate esters (www.envstd.com/you-mean-my-dro-datamay-not-be-from-diesel-fuel, accessed June 2016).

Consistent trace levels of DRO and RRO were found across all sites and sample events (Figure B14), with DRO typically 50 – 100 µg/L and RRO 100 – 175 µg/L. Exceptions were elevated concentrations of both in Feb 2014 samples from Sahdoanah Creek (SDN), which could perhaps reflect contamination from the upstream gas compressor facility in the watershed. Similarly elevated levels were found in May 2012 samples from Courvoisier Creek (CRV05).

Complete identification of detected components, as was done by Drollette et al. (2015) would greatly enhance the utility of these rather non-specific analyses and should be conducted in future work. The levels measured here represent trace contamination, whether due to natural or industrial sources. Should further water quality work in the area proceed, some additional sampling to determine background DRO and RRO in unaffected watersheds is recommended.

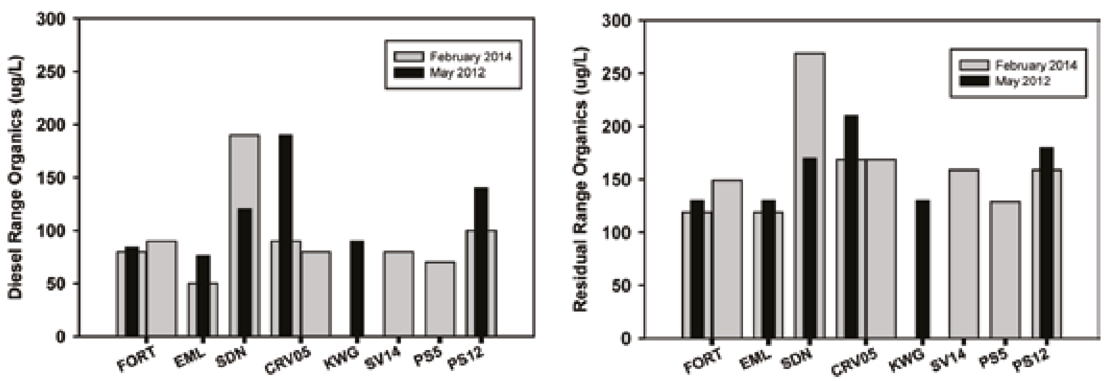


FIGURE B14. *Diesel-range and residual-range organics in water samples from select sites in the Horn River Basin in May 2012 and in February 2014.*

Naphthenic acids
Naphthenic acids are a mixture of carboxylic acids containing one or more saturated acyclic rings (Headley and McMartin 2004, Clemente and Fedorak 2005, Speight 2014). These may be produced naturally through aerobic microbial digestion of petroleum (Meredith et al. 2000) or coal (Scott et al. 2009), and so are frequent contaminants in oil or gas-bearing geologies. Naphthenic acids are a particular concern in the Alberta Oil Sands area where tailings pond waters may be as high as 110 mg/L (Headley and McMartin 2004). Naphthenic acids have a number of industrial applications, including as additives for cutting oils in oil and gas drilling. As such, they may be present in drilling muds and fluids, and are present in gas well return flows which may make their way to surface waters (USEPA 2015).

In view of the low and/or transient levels of NAs expected in the study area, an initial sampling using POCIS was conducted during freshet in May 2012. The results are presented in Figure B15. It is important to understand that although concentrations per sampler are shown, the results should be interpreted a "*presence*" or an "*absence*" at the sites. Naphthenic acids were clearly evident at four of the five sample sites, and were apparently absent at Fortune Creek.

Subsequent grab samples were collected in August 2014. In sharp contrast to the POCIS results, total NAs in Fortune Creek were clearly elevated against what seems a regional background of approximately 2 µg/L (Figure B16).

Some caveats need be mentioned in examining the few NA results presented here. Naphthenic acid determination in environmental samples is challenging (Brown and Ulrich 2015) and analytical methods have been progressing rapidly in recent years. Some methods do not determine the full suite of congeners and relevant calibration standards are not available – issues which have caused ECCC to consider all NA results to be "semi-quantitative". The method used in analyses conducted in this work (Woudneh et al. 2013) includes a multi-step workup including acidification, derivatization and preconcentration by rotary evaporation all of which have some challenges and potential interferences. As well, some carboxylated natural compounds, including resin acids, fatty acids and some humic acids could contribute to false positives (Brunswick et al. 2016). Brown and Ulrich (2015, Table 1) presented data showing the consequence of analytical methods used in NA determinations, with paired surface water samples occasionally having concentrations differing by an order of magnitude or more.

The results presented here suggest the presence of low levels of NAs. Should further sampling and analysis proceed, measurements should employ newly available and highly specific LC/QToF (i.e. Brunswick et al. 2015) or other high resolution mass spectrometry techniques recommended by the experts in this field in a 2016 workshop organized by ECCC (Dayue Shang, Environment and Climate Change Canada, *pers. comm.* Oct 2016) to reduce the necessary sample treatment and potential confounding factors.

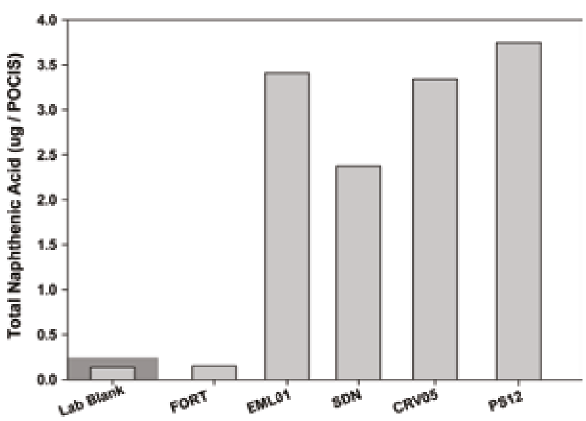


FIGURE B15. *Results of POCIS sampler deployment during high water (May-June 2012). Note that concentrations are qualitative; expressed as total µg per sampler. Lab blank shown at left for QA comparison.*

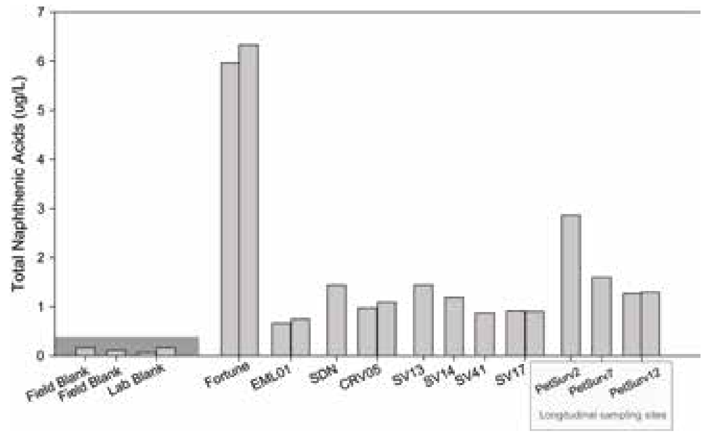


FIGURE B16. *Total naphthenic acids in grab samples collected at select sites in August 2014. Paired bars are duplicate samples; QA sets (travel blanks; lab blanks) are shown at left.*

Polycyclic Aromatic Hydrocarbons

Grab samples for analysis of PAH compounds were collected on three occasions; once during high water in May 2012, and in two subsequent samplings during low flow – October 2013 and August 2014. Polycyclic aromatic hydrocarbons are indicators of natural and anthropogenic petroleum contamination and have both biogenic and combustion sources (Yunker and McDonald 1995). Patterns in ratios of parent to alkylated components, as well as concentrations of individual PAH congeners can provide clues to the particular contamination sources.

Polycyclic aromatic hydrocarbons tend to have low solubility, so total PAH concentrations as well as congener composition are closely tied to total suspended solid load (Boehm 2005). In high water samples (Figure B17), total PAH concentrations were 10 times higher than in low flow samples (Figure B18), which mirrors other similar studies comparing total and dissolved PAHs (McCarthy et al. 1997). Total PAHs from the six sites tended to fall between 40 – 60 ng/L, the exception being a sample from Sahdoanah Creek at 120 ng/L (Figure B17). Low water total PAH concentrations ranged from about 2 – 6 ng/L, with the exception of samples at the SDN, CRV and PS2 locations (Figure B18).

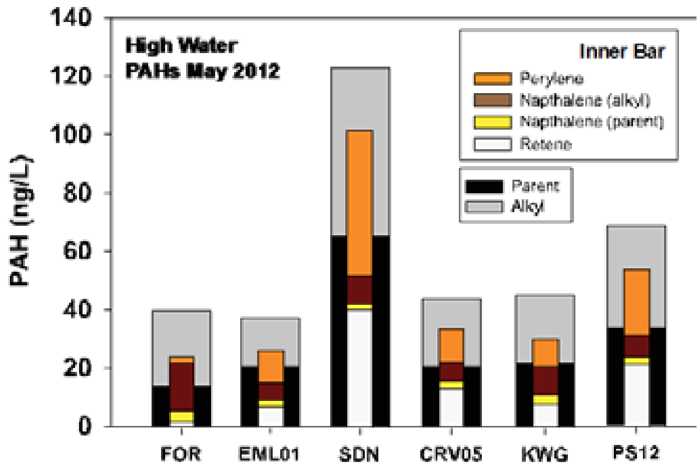


FIGURE B17. *Summary PAH results for high water samples at select sites in May 2012. Black and grey background bars show relative contributions of parent and alkyl PAHs to the total PAH concentrations. Inner stacked bars indicate concentrations of selected individual parent and alkylated components contributing to the total PAH concentrations.*

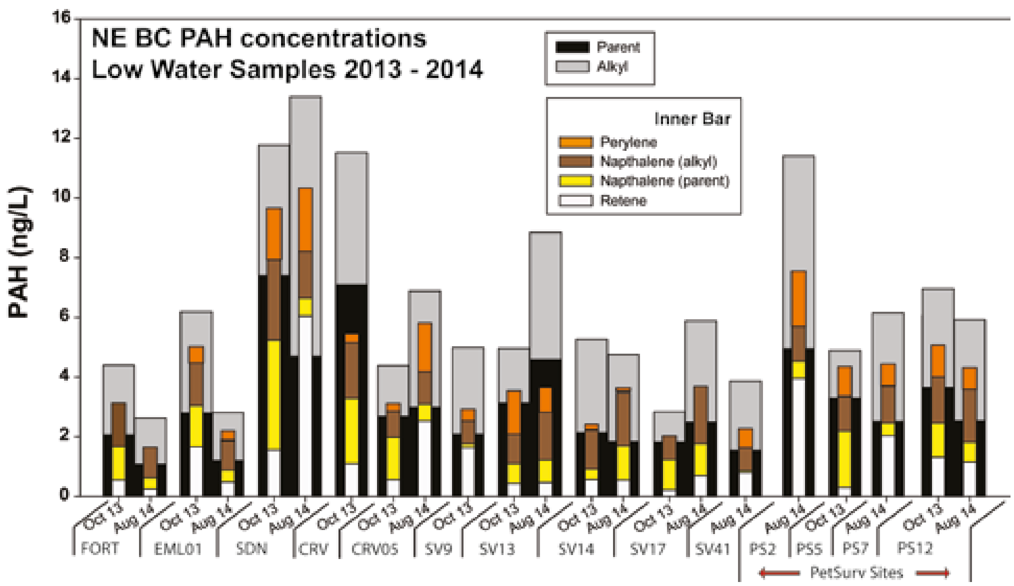


FIGURE B18. *Summary PAH results for low water samples in 2013 and 2014. Black and grey background bars show relative contributions of parent and alkyl PAHs to the total PAH concentrations. Inner stacked bars indicate concentrations of selected individual parent and alkylated components contributing to the total PAH concentrations.*

The inset stacked bars in Figures B17 and B18 show the contributions of select PAH components, each of which has either biogenic or indirect biogenic origin (Wilcke 2007). Perylene is a naturally occurring PAH generated by bacterial degradation and is a component of bogs and wetlands (Wakeham et al. 1980, Wilcke 2007, Yudina and Savel'eva 2011). Naphthalene and some alkyl-naphthalenes were important contributors to the total PAH levels in the low water samples (Figure B18). This is perhaps a reflection of their relatively high solubility compared to other PAH congeners. While naphthalene and other low molecular weight PAHs can result from spills of unburned petroleum fuels, there is some evidence that they may also be produced by bacteria and fungi (Wilcke 2007). Retene is an established indicator of wood burning (Ramdahl 1983) and occurs at elevated levels after wildfires (Gabos et al. 2001). A relationship between measured retene levels in these analyses and recent forest fires in the upstream watershed is weakly evident though highly variable (Figure B19).

Total PAH concentrations reported here are low compared to published dissolved PAH measurements in populated and industrialized areas (Manoli and Samara 1999, Santana et al. 2015). Levels are similar to results of recent sampling in headwater drainages in the UK, with reported concentrations from 2.1 – 16.8 ng/L (Moeckel et al. 2014), and are generally lower than levels measured in the Slave River in the Northwest Territories reported by McCarthy et al. (1997). Measuring organic compounds in surface

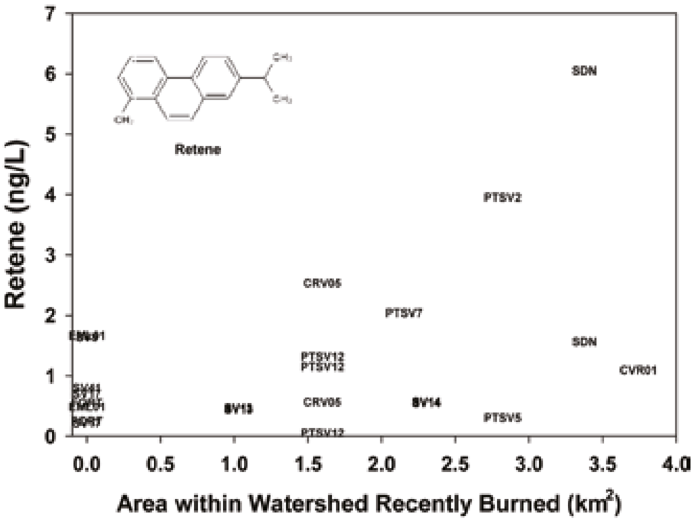


FIGURE B19. *Relationship between total area recently (2003-2013) burned in wildfire within each watershed and measured retene concentration in low water samples collected in October 2013 and August 2014.*

waters and attributing their presence unequivocally to contamination from UOG activity will be very difficult because of their low concentrations in natural surface waters already containing a wide range of potentially interfering natural organic compounds. There is a particular challenge in even determining the suite of organic contaminants to be analyzed given the proprietary composition of fracking fluids. Budget is of some concern, because low-level organic analyses can be very expensive and too often return data tables with non-detections. Unless a suitable target indicator is available, the approach more likely to detect surface-water contamination is that taken in the core synoptic program, with analysis of inorganic constituents known to be at extreme concentrations in produced waters (Vidic et al. 2013, Brantley et al. 2014).

B2.4 RELATIONSHIPS BETWEEN WATER QUALITY AND GAS FACILITIES

A key component of the study design was measurement of water chemistry at locations near the outlets of microbasins having a range of upstream UOG activity. Using the delineated watershed boundaries upstream of the sample sites and georeferenced oil and gas facilities data available from the BCOGC, counts of total numbers of wells (active or abandoned), drill waste disposal area, numbers of facilities and the number of waste disposal sites were determined. Should industrial activities in the upstream watershed be affecting downstream water quality, there would be a positive relationship between one or more of BCOGC activity variables and some key components of the water chemistry.

Correlations between key physical-chemical indicators of hydraulic fracturing and some measures of upstream industrial activity at high and low flow periods are presented in Table B3. The high flow (freshet) sampling data show low ($r_s \sim 0.47 – 0.57$) but significant correlations between the total number of facilities and the number of disposal sump sites and total barium and total suspended solids. Barium in particular shows correlation with two of the BCOGC categories, and together with TSS is related to the number of disposal sump sites. The association of TSS and barium in this instance might be expected since there is a high correlation between the two variables in the high flow dataset ($r_s = 0.73$, $p<0.001$). Since Ba concentration is known to be elevated in drilling wastes (Renock et al. 2016), and since much of the drilling activity is conducted in winter (CCA 2014), it is possible that elevated TSS with associated barium could be resulting from mobilization and overland transport by meltwater flows. Similar results have been reported elsewhere; a large-scale study in the northeast United States found a significant relationship between well densities and TSS (Olmstead et al. 2013). Plots of the relationships between BCOGC categories and TSS and total barium concentrations are shown in Figure B20. Weak correlations amongst BCOCG categories and dissolved sulphate (Table B3, Figure B20) and dissolved chloride (Table B3) were evident as well, again related to drill waste-associated variables.

TABLE B3. *Spearman rank correlations and associated probabilities at smaller (non-Petitot River mainstem) basins between select water chemistry variables and watershed UOG activity data as determined from BCOGC GIS layers. BCOGC data were extracted to reflect facility and disposal area counts just prior to water quality sampling in each year. Significant values highlighted in* ***bold.***

		HIGH WATER (N=27; 2013-2014)				LOW WATER (N=46; 2012-2014)			
		TOTAL FACILITIES	DRILL WASTE DISPOSAL AREA	TOTAL NUMBER OF WELLS	# DISPOSAL SUMP SITES	TOTAL FACILITIES	DRILL WASTE DISPOSAL AREA	TOTAL NUMBER OF WELLS	# DISPOSAL SUMP SITES
Dissolved Chloride	r_s	0.00	0.17	0.27	0.25	0.04	0.21	0.14	**0.31**
	p	0.991	0.404	0.172	0.199	0.786	0.179	0.354	**0.040**
Dissolved Sulphate	r_s	0.27	0.28	0.22	0.20	0.23	**0.32**	0.17	0.25
	p	0.170	0.162	0.264	0.327	0.131	**0.035**	0.268	0.099
Total Suspended Solids	r_s	0.12	0.11	0.07	**0.47**	0.20	0.28	0.28	0.15
	p	0.551	0.582	0.729	**0.013**	0.200	0.071	0.070	0.340
Specific Conductance	r_s	0.30	0.19	0.20	0.30	0.04	0.08	0.04	0.14
	p	0.126	0.346	0.304	0.126	0.799	0.589	0.802	0.381
Total Barium	r_s	**0.48**	0.33	0.21	**0.57**	0.13	0.13	0.13	0.21
	p	**0.011**	0.092	0.293	**0.002**	0.383	0.402	0.383	0.162
Total Boron	r_s	0.29	0.19	0.16	0.33	-0.05	0.07	-0.03	0.19
	p	0.135	0.330	0.415	0.097	0.741	0.639	0.847	0.225
Total Strontium	r_s	0.29	0.17	0.17	0.32	-0.03	0.03	-0.04	0.07
	p	0.142	0.383	0.397	0.103	0.840	0.824	0.819	0.664
Sodium	r_s	0.16	0.00	-0.01	0.15	-0.08	-0.05	-0.11	0.13
	p	0.413	0.994	0.974	0.460	0.605	0.760	0.486	0.407

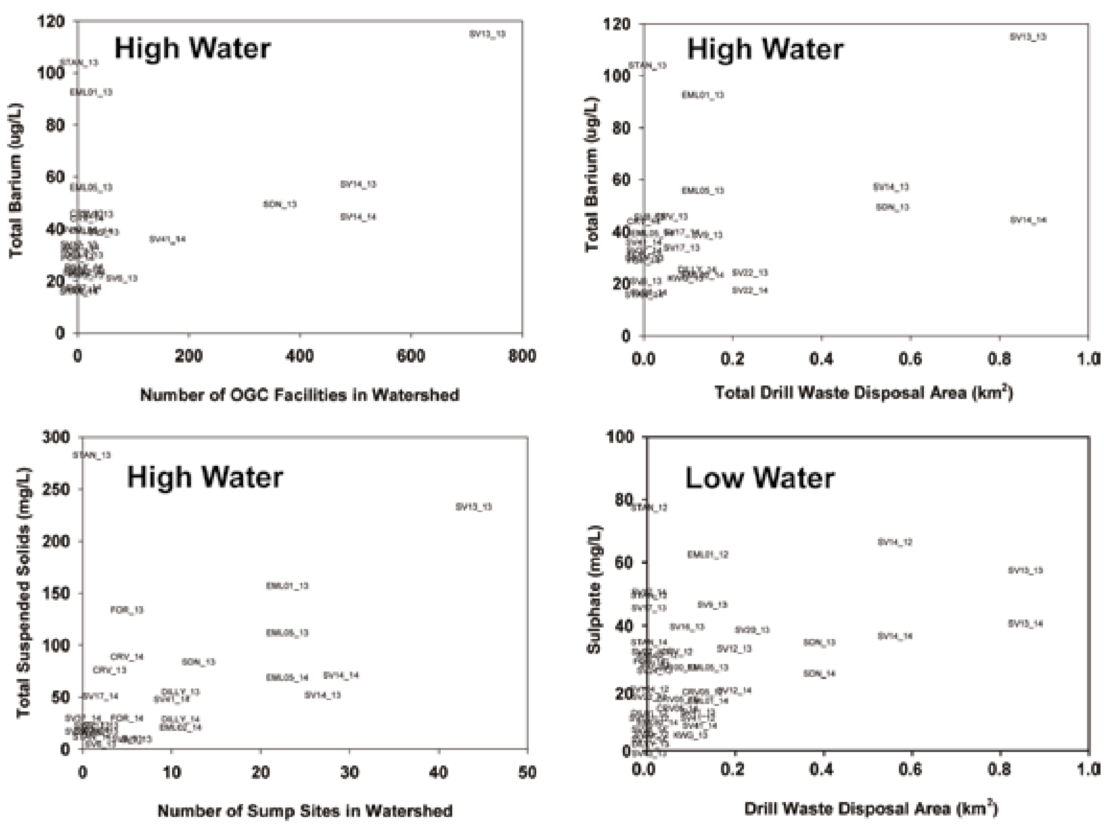


FIGURE B20. *Plots of water quality and BCOGC UOG activity variables with significant (p <0.05) Spearman Rank correlations for both high and low water water data. Plotted points show the sample location and year; for example SV14_13 represents results from site SV14 collected in 2013.*

The magnitude of correlations here are relatively low, but given the coarse approach and the sparse data, the pattern suggest some effect of gas extraction on surface water quality. Road construction, seismic lines, well pad, and land clearing might be expected to result in increased TSS loading and the magnitude should be proportional to the extent of the activity. Large-scale studies of effects of gas extraction activities on surface water have shown similarly equivocal results. In the eastern United States, treatment of shale gas wastewaters resulted in increases in Cl levels as a consequence of discharged water treatment effluents and not as a direct release from well sites (Olmstead et al. 2013). Statistical analysis of trends in Cl and conductivity have proven notoriously difficult to interpret in relation to fracking activity (Bowen et al. 2015).

Gas development involves significant surface modification and disturbance, including seismic lines, roads and well pads and much of this is occurring during the winter months when ground is firm enough to carry large machinery. The combination with elevated barium as well could be suggestive of drill waste, though much more work would be required to explore this possibility. An additional complication in interpreting these results is that some basins from which samples were collected are nested, particularly in the southern drainage to the Fort Nelson River (Figure B21).

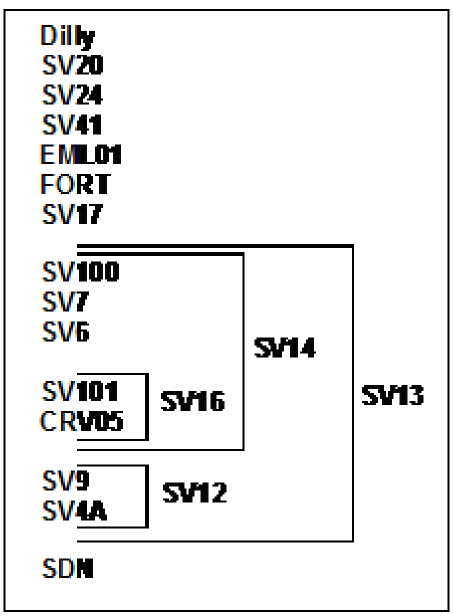


FIGURE B21. *Schematic illustrating the inter-nesting of sampled watersheds.*

Water quality monitoring by regular grab sampling is presently the only method to study temporal changes of a wide range of chemical variables. Until sensor technologies progress and a broader spectrum of chemicals are measurable reliably and at low concentrations, automated monitoring will be largely restricted to reliable and robust measurements such as conductivity and temperature. Logger deployments in the northeast BC area would provide continued cost-effective monitoring in conjunction with grab sampling.

The search for an ideal indicator or suite of indicators has been elusive. Some authors have shown promise in the use of isotopic indicators, such as ^{11}B and ^{7}Li (Warner et al. 2014) or ratios of stable isotopes of Sr (Warner et al. 2013), and may have some utility in future work in northeast BC.

B3. CONCLUSIONS AND RECOMMENDATIONS

- Patterns in water chemistry in the mainstem Petitot River showed no indication of upstream contaminants, perhaps because of the relatively high volume and potential dilution of constituents which might have been present at elevated concentrations in tributary streams. In the smaller watersheds, there were potential indications of the effects on surface water chemistry of upstream UOG activity.
- A few of the specific UOG indicator variables that were the particular focus of this interpretation – Ba, SO_4, Cl, TSS – showed some weak correlations with oil and gas facilities and operations. Barium especially showed a relationship in freshet conditions with BCOGC variables related to drill waste, though further work would be needed to properly assess this.
- Trace organic analyses showed undetectable or low background concentrations for all measured analytes. While there were no strong indications of upstream industrial contamination, some further work on NAs might be warranted.

Suggestions for future work in northeast BC:

- Chemical analyses of produced waters need to be made available to the environmental research and regulatory community. These analyses need not identify the specific proprietary composition of injected fracking fluids, but should be sufficiently comprehensive to guide monitoring activities.
- Monitoring sites need to be established at outlets of smaller basins containing upstream oil and gas developments and be carefully tracked as expansion proceeds. Here again, the suite of chemical variables would be selected from measurements of produced waters.
- A network of paired temperature and conductivity loggers which could remain in situ for extended periods should be established. These would detect transient contamination by upstream releases, such as produced waters having extreme TDS.

PART C
BIOLOGICAL WATER QUALITY MONITORING

C1. METHODS

C1.1 STUDY DESIGN AND SITE SELECTION

The biological monitoring study design follows Canadian Aquatic Biomonitoring Network (CABIN) methodology, based on benthic macroinvertebrate data gathered in stream and rivers (Environment Canada 2012 www.ec.gc.ca/rcba-cabin/). To develop a bioassessment model for the assessment of streams affected by UOG activity a wide range of natural variation of biota and habitat must be collected from a range of reference or minimally disturbed sites. Based on these data and following the reference condition approach (Bailey et al. 2004), the predictive bioassessment model is developed to provide an empirical definition of ecosystem health where the biological community at a given site can be predicted by natural habitat features. The degree of divergence of the observed benthic community from the predicted community is an indication of the degree of the environmental stress (Reynoldson et al. 2001).

Prior to the initiation of this study, benthic macroinvertebrate data were collected following the CABIN protocol by BC Ministry of Environment and GeoScience BC www.geosciencebc.com) through Environmental Dynamics Inc. (www.edynamics.com/) in 2010 and 2011 and then again in 2012. The suitability of these sites for inclusion in the bioassessment model was evaluated *post hoc* based on methodology outlined below.

The geographic scope of the bioassessment model was limited to the boundaries of Liard River Basin within BC including the Petitot River and the lower Fort Nelson River (Section 4, Figure 4). Stratification of potential reference sites, sites unaffected or minimally influenced by human activity, focused on three of the five ecoregions surrounding the Horn River Basin: the Northern Alberta Uplands, Hay River Lowlands and the Muskwa Plateau (Section 4, Figure 5) and focused on classification of the study area based on surficial geology. The objective was to stratify the sampling effort over the range of natural variation with a goal of two to three sites within each geology type within each ecoregion and stream order. To capture temporal variation in the bioassessment model a subset of reference sites were also sampled in multiple years. It has been suggested that 60-75 sites are required to develop a model (Reynoldson and Wright 2000) but is dependent on the ecological variation of the area of interest.

To objectively select potential reference sites, a four step process employing the Human Activity Gradient (HAG) (Yates and Bailey 2010) was employed and potential reference microbasins were randomly selected for sampling with prioritization on sites in close proximity to the Horn River Basin (see below). In addition, test sites, sites exposed to UOG activity, were sampled to assess the potential effects of UOG activity on the health of the aquatic ecosystem. Test sites were sampled across a gradient of well densities and co-located with routine or synoptic monitoring locations where possible.

Step 1 – Determining Natural Stratification: Microbasins, polygons delineated using the 1:50K stream network that are 3rd order and higher (BC Freshwater Atlas, Appendix Table C1), were identified for the study area. K-means cluster analysis was performed on the surficial geology of the microbasins. The optimal number of clusters was determined by looking at where the within and among variation for two to eight natural groupings was maximized through two analyses a) Elbow test of the K-means results for each clustering option (i.e. Between SS/Total SS), and b) discriminant function analysis (DFA) of each cluster option as a factor to describe the surficial geology to find the largest differences among the group means (i.e. lowest Wilk's Lambda).

Step 2 – Establishing Stressor Gradient: The extent of oil and gas activities in each natural grouping were quantified using current stressor variables acquired from GIS data from the BCOGC related to wells, facilities, disposal sites, roads, and pipelines (Appendix Table C1). Stressor variables were separated into three stressor types to reduce the number of variables to a single variable through principle component analysis (PCA):

1. facilities (BC waste disposal-area, facility water disposal/injection, other facility),
2. wells (all well variables),
3. networks (pipeline area, roads-winter, road-all season).

The first component scores from each of the 3 PCAs were combined into a second PCA to describe a single oil and gas stressor for the area using the first component score. From this component score criteria were established for reference sites.

Step 3 – Pre-sampling – Defining Reference Criteria and Selecting Potential Sites: Microbasins without human influence within each natural grouping were identified as potential reference sampling locations. Minimally disturbed areas were defined in natural groupings which tended to have UOG activity. The reference microbasins were further stratified within each grouping by stream order and ecoregion. Potential reference microbasins were randomly selected for field verification.

Step 4 – Field & Post Sampling – Reference Site Selection and Verification: Actual sampling locations were ultimately chosen based on helicopter access and suitability for CABIN sampling. Reference condition was verified via aerial reconnaissance. Also, BCOGC geospatial data dated to mid-August of each year (Table C3) were evaluated post sampling. If UOG activity stressors were found in the upstream watershed from the post-sampling confirmation, the site status was changed to a test site and removed from the model development process.

C1.2 SAMPLE COLLECTION

At each site a single integrated benthic macroinvertebrate sample was taken according to the CABIN protocol (Environment Canada 2012, http://www.ec.gc.ca/rcba-cabin/) during late summer and preserved with 10% buffered neutral formalin. Local habitat characteristics (i.e. substrate size, slope, velocity, depth, width and riparian vegetation) were also measured and recorded according to the CABIN protocol. In accordance with the water quality components of this project, a suite of basic physical chemical variables in water were also taken (Figure C1).

Macroinvertebrate samples were processed following the protocols outlined in the CABIN laboratory manual (Environment Canada 2014a) by Cordillera Consulting, Summerland, BC or EcoAnalysts, Moscow, Idaho. Organisms were identified to genus or species where possible and entered into the CABIN database. Ten percent of all invertebrate samples were audited by the National Laboratory to ensure CABIN criteria for sorting efficiency and identification error rates were met.

Upstream basin delineations specific to the sampling locations were obtained using Digital Elevation Model (DEM) data in raster format, corresponding to the 1:50K NTS (25 m cell size) National Hydro Network map sheets. Geospatial data layers specific to the upstream drainage area were acquired to generate landscape level variables related to hydrology, topography, morphometry, geology, climate, land use, transportation, and UOG.

All data were collected by CABIN certified staff and validated to ensure observed differences were not due to operator variability and entered into the CABIN database (www.ec.gc.ca/rcba-cabin/).

FIGURE C1. *Images of sampling conducted during the biological monitoring component in northeast BC where macroinvertebrates are collected with a kicknet and other habitat characteristics are measured. Photos by Patrick Shaw and Stephanie Strachan.*

C1.3 DATA ANALYSIS

Model development

Model development followed the Benthic Assessment of SedimenT (BEAST) approach (Reynoldson et al. 1995). Biological structure of the raw family-level data was determined through cluster analysis and multidimensional scaling (MDS) ordination on a Bray-Curtis similarity matrix using PRIMER version 6.1.12 (Primer-E 2009). The data were not transformed as the numeric differences were considered to be an important difference among the biological groups (Reynoldson et al. 1995). Using the SIMPROF analysis in PRIMER, a significance test for structure in the data involving a series of permutation tests was performed comparing the ranked resemblance matrix with randomised matrices to look for significant grouping structure. Groups with fewer than 10 sites have been suggested to be too small (Reynoldson et al. 2001). After close examination of the raw data and similarity to neighbouring sites in the dendrogram, small groups were either left as outliers or rolled up with the next most similar group if they were similar in habitat, or left as a small group if they were clearly a unique cluster requiring more sampling.

More than 100 local and landscape habitat variables unaffected by human disturbance were identified as candidate predictor variables and were reduced to a smaller suite by correlation analysis. Stepwise DFA was used on the reduced suite using both forward and backward procedures to derive a list of the most likely predictor variables. The stepwise models then were iteratively revised adding and removing variables based on tolerance scores (the proportion of a variable's variance not accounted for by other independent variables) and F values to achieve the optimal model. The optimal model had the lowest Wilks' λ (smaller values of Wilks' λ indicate greater discriminatory ability) with a maximum number of variables being no more than the number of sites in the smallest group.

An optimal model has the highest possible overall cross-validation rate with similar individual group error rates and the fewest possible variables. The cross-validation classification rate is based on the model being built from all the data several times with a different reference site being removed from the analysis each time, while the resubstitution rate is simply based on reclassifying each reference site using the model but without removing it from the model building process. The cross-validation rate is always lower than the resubstitution rate but is a better test of the model predictions.

Model evaluation

Model performance was assessed using simulated disturbance data, which provided an estimate of Type 1 (mistakenly determining a reference site is impaired) and Type 2 (not detecting impairment at an impacted site) error rates for different disturbance intensities (Bailey et al. 2012). Widely accepted Hilsenhoff's family level tolerance scores are available to generate simulated data (Barbour et al. 1999) which reflect sensitivity to oxygen depletion (eutrophication) but are not relevant to potential impacts from this industry. Therefore, CABIN records in British Columbia were used to generate a novel resource development tolerance score (RDT) describing expected changes to the stream environment caused by resource development to generate simulated disturbance data. The generation of the RDT is based on a similar approach used in the Yukon Territory (Reynoldson et al., GHOST Consulting, *pers. comm.* June 2016). The new RDT was intended to reflect taxa tolerance to habitat alteration, fining of substrate, and increased turbidity caused by increased erosion through corridor construction and facility use. For example, macroinvertebrate taxa in BC that were frequently associated with boulder substrates and low embeddedness were expected to be sensitive to increases in sandy/silty substrates and embeddedness.

Developing the RDT took advantage of the approximately 3500 CABIN records in BC (http://ec.gc.ca/rcba-cabin/ accessed June 2015), correlating 170 benthic macroinvertebrate families with nine habitat variables related to substrate and disturbance. For each habitat variable, taxa were considered potentially sensitive, tolerant, or insensitive based on the direction and degree of correlation. The taxa with the strongest correlations (to a maximum of 40) were designated tolerant and sensitive (depending on the expected response for each variable; Table C1), and the remaining taxa designated insensitive. The RDT for each family defined its position on a *Tolerant→Insensitve→Sensitive* continuum, scaled from +1 (highly tolerant) to -1 (highly sensitive) based on the number of variables on which it was ranked in each tolerance category. The RDT was relative and did not reflect the strength of habitat variable correlations in absolute terms.

To simulate the effect of disturbance on northeast BC reference communities, the RDT was applied to the entire reference dataset to generate simulated assemblages representing three different intensities of disturbance. The RDT of each taxon was multiplied by its abundance at each reference site and multiplied by the simulated intensity factor (1, 2, or 3), then added to the original abundance of that taxon (i.e. Abundance + [RDT * Abundance * Intensity factor]). Where calculations resulted in a negative abundance for a particular taxon (e.g. sensitive taxa were eliminated from the community), the negative values were replaced with a 0 value.

TABLE C1. *Expected response variables representing potential UOG development impacts in the Shale Gas development area of BC and the expected correlations with tolerant or sensitive taxa.*

RESPONSE VARIABLE	DEVELOPMENT-SENSITIVE TAXA CORRELATION	DEVELOPMENT-TOLERANT TAXA CORRELATION	INSENSITIVE TAXA CORRELATION
Total Suspended Solids	**Negative**	**Positive**	**None**
Turbidity	**Negative**	**Positive**	**None**
Bedrock %	**Positive**	**Negative**	**None**
Boulder %	**Positive**	**Negative**	**None**
Gravel %	**Negative**	**Positive**	**None**
Sand %	**Negative**	**Positive**	**None**
Silt/clay %	**Negative**	**Positive**	**None**
Embeddedness[1]	**Positive**	**Negative**	**None**
Dominant Substrate[2]	**Positive**	**Negative**	**None**

[1] Note: CABIN data is entered such that a low embeddedness score means high actual embeddedness so the correlation appears opposite.
[2] In the CABIN database, larger categories indicated larger dominant substrates so the correlation appears opposite.

Test site assessment

Several sites with known exposure to various UOG activities were chosen as test sites to evaluate current status of aquatic ecosystem health. Test sites were predicted to the appropriate reference groups using the required habitat characteristics in the preliminary model, and their benthic macroinvertebrate communities were compared to the respective reference communities. The observed invertebrate community at the test site was plotted in ordination space based on Bray-Curtis dissimilarity with the predicted group of reference site communities and three confidence ellipses were constructed on the ordination scores of the reference sites to provide four assessment categories for the test site community. Test sites were assigned an overall degree of divergence from the expected condition (i.e. similar to reference, mildly divergent, divergent, and highly divergent) based on their distance from reference in ordination space.

C2. RESULTS AND DISCUSSION

C2.1 DETERMINATION OF REFERENCE SITES

Step 1 – Determining Natural Stratification: A total of 961 microbasins with less than 0.05% urban cover were considered in the initial stages of the exercise. After evaluation of the within and among variation of the surficial geology of the microbasins clustered into two to eight groups (based on K-means clustering) using both an elbow test and DFA, five natural groupings were identified as the best natural stratification of the microbasins in the study area (Figure C2).

Step 2 – Establishing Stressor Gradient: Following individual and combined PCA analysis of three different stressor types (facilities, wells and linear networks) for each grouping, the first tier of reference sites (best available) was defined as having a 0 score on the first component of the combined PCA scores where minimal stressors exists. The second tier of reference sites (next best with minimal exposure) would have a low score on the first component from the combined PCA but have a zero score on at least 1 of the first components from the individual stressor type PCAs.

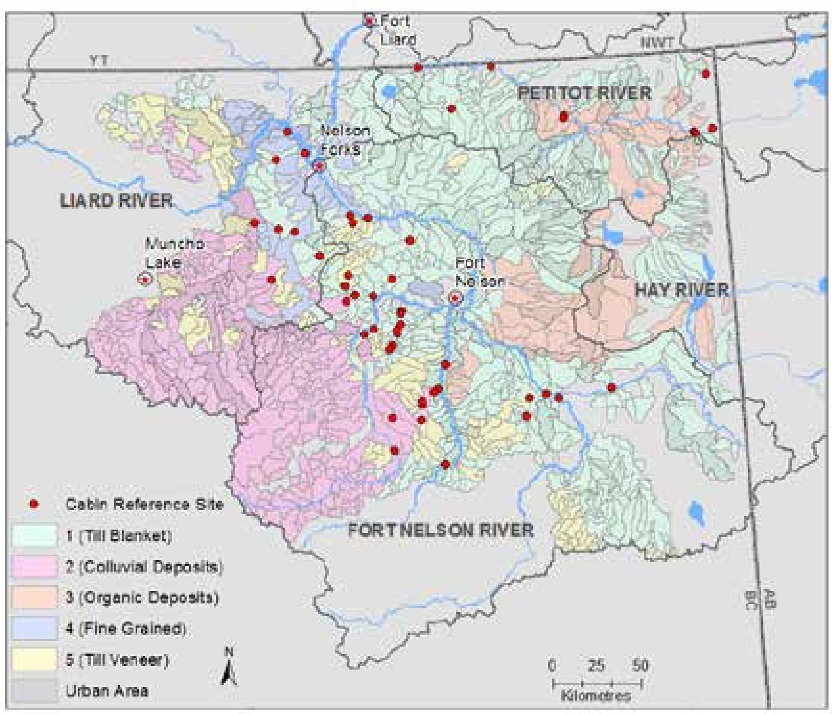


FIGURE C2. *Identification of five natural groupings of microbasins based on surficial geology to stratify reference site selection in the study area.*

Step 3 – Pre-sampling – Defining Reference Criteria and Selecting Sites: Three of the five natural groupings had limited UOG activity or human influence. Exceptions include Group 1 (microbasins dominated by till blanket) and Group 3 (microbasins dominated by organic deposits). Reference site criteria related to these stressors were defined as the maximum value from the 1st and 2nd tiers of identified reference microbasins from the stressor gradients for each natural grouping (Table C2). The final number of microbasins in each natural grouping identified as potential reference are shown in Table C3.

TABLE C2. *Reference site criteria for the five natural groupings as determined by the HAG based on maximum values from Tier 1 and Tier 2 microbasins.*

	GROUP 1	GROUP 2	GROUP 3*	GROUP 4*	GROUP 5
Active/Completed/Suspended well density (wells/km^2)	0.006**	0	0	0	0
Other well density (wells/km^2)	0.024	0	0.03	0.0005	0.002
Waste disposal (facilities/km^2)	0	0	0	0	0
Facilities (facilities/km^2)	0.002	0.0003	0	0	0
Stream crossings (count/km^2)	0.004	0	0.015	0	0
Changes near the stream (count/km^2)	0.005	0	0.002	0	0.0001
Short term water uses (count)	0.011	0	0	0	0
Road Density (includes winter roads) (km/km^2)	0.11	0.009	0.010	0.003	0.014
% Pipeline area	0.196%	0%	0%	0%	0%

* Tier 2 microbasins did not exist
** Presence of some wells accepted if >20 river km from sampling site or if older than 2006 (prior to horizontal fracturing operations in the Horn River Basin)

TABLE C3. *Number of microbasins in the five natural groupings identified through cluster analysis of landscape natural features, number and proportion of sites which met reference site criteria for inclusion in preliminary model.*

	GROUP 1	GROUP 2*	GROUP 3	GROUP 4	GROUP 5
Total identified	463	236	88	28	147
# microbasins meeting reference criteria	126	228	11	15	93
Proportion of group identified as reference	27%	97%	12.5%	54%	63%
Proportion of group represented in model	12.74%	4.7%	7.95%	17.86%	28.53%

* Most of this group falls into ecoregions outside of our focused area and outside of oil and gas activity

Step 4 – Field & Post Sampling – Reference Site Verification: The CABIN methodology is intended for wadeable lotic habitats. In many cases helicopter access for randomly chosen microbasins was too difficult or water was stagnant. Locations were moved elsewhere in the watershed or to the next randomly chosen microbasin. Post-sampling, UOG-activity based on BCOGC geospatial data dated to mid-August of each sample year was reviewed and drainage areas upstream of the sampling location were evaluated according to well and waste-disposal activity (Table C4) to confirm reference site status.

After site verification and after applying all of the above stressor criteria to the sampled sites, a total of 53 reference sites were confirmed for this bioassessment model distributed among most stream orders and ecoregions (Table C5). As expected, all stream order 1 sites were impossible to sample and most stream order 2 sites were difficult to find. Data gaps remain for reference sites for Natural Grouping 3 (organic deposits) and 4 (fine grained). Larger streams (i.e. stream order 5 and 6) in reference condition are difficult to find, however a total of 11 sites on stream order 5 and 6 were sampled with data gaps in all natural groupings. Sites were evenly distributed among the Hay River Lowlands and the Muskwa Plateau ecoregions however there were some data gaps within the Northern Alberta Uplands ecoregion. As a result of the data gaps, the bioassessment model in this report will be considered preliminary until more reference sites can be sampled to ensure the full range of ecological variation is captured.

TABLE C4. *Description of the stressor activity of the sampled reference sites relative to the identified microbasins in the study area based on BCOGC geospatial data variables.*

	REFERENCE MAXIMUM	REFERENCE AVERAGE	RANGE OF MICROBASINS (REFERENCE + NON-REFERENCE)
Active/Completed/Suspended well density since 2006* or wells <20 km site (wells/km^2)	**0**	**0**	**0-247**
Other well density** (wells/km^2)	**0.08**	**0.006**	**0-0.83**
Waste disposal (facilities/km^2)	**0**	**0**	**0-0.61**
Facilities (facilities/km^2)	**0.05**	**0.003**	**0.79**
Stream crossings (count/km^2)	**0.06**	**0.002**	**0-1.70**
Changes near the stream (count/km^2)	**0.02**	**0.002**	**0-1.74**
Short term water uses (count)	**8**	**0**	**0-27**
Road Density (includes winter roads) (km/km^2)	**0.18**	**0.03**	**0-1.51**
% Pipeline area	**0.0015%**	**0.0001%**	**0-0.196%**

* Based on reported initiation of horizontal fracturing in the Horn River Basin (NRCAN accessed October 2017 http://www.nrcan.gc.ca/energy/sources/shale-tight-resources/17677).
** Other well activity permitted for reference selection criteria based on BCGOC geospatial data well classification includes: testing, authorized, cased, abandoned, drilled, undefined.

TABLE C5. *Distribution of the number of reference sites sampled among natural groupings by stream order (SO) and ecoregion.*

	ECOREGION	NATURAL GROUPING					
		1	2	3	4	5	GRAND TOTAL
SO2	Hay River Lowland	2	1				**3**
	Northern Alberta Uplands	1					**1**
SO3	Hay River Lowland	3		1			**4**
	Muskwa Plateau	1	3		2	1	**7**
	Northern Alberta Uplands	4		2	1	1	**8**
SO4	Hay River Lowland	5	1			1	**7**
	Muskwa Plateau	3	2			6	**11**
	Northern Alberta Uplands	1					**1**
SO5	Hay River Lowland	4				1	**5**
	Muskwa Plateau	1	1				**2**
SO6	Northern Alberta Uplands			4			**4**
Grand Total		**25**	**8**	**7**	**3**	**10**	**53**

A total of 33 sites were determined to have some level of UOG activity. ECCC sampled 26 test sites between 2012 and 2014 and 7 test sites were collected by BC Ministry of Environment or Environmental Dynamics between 2010 and 2012. Seven of the test sites were sampled in multiple years to evaluate temporal and assessment variability (Table C6). In addition, three reference sites were sampled in multiple years to ensure temporal variability was incorporated into the bioassessment model (Table C6).

TABLE C6. *List of sites sampled in more than one year to assess temporal variability (reference sites) and assessment variability (test sites).*

STREAM NAME (SITE-CODE)	STATUS	YEARS SAMPLED (AGENCY)
Upper Petitot River (PET08/UPET002)	Reference	2011 (BCMOE); 2012, 2013 (EC)
Stanolind Creek (STND02/Stanolind Cr)	Reference	2012 (EC); 2013 (EDI)
Tributary to Petitot River (TSE06/PET06)	Reference	2012, 2013 (EC)
Petitot River at Highway 77 (PET01)	Test	2012, 2013, 2014 (EC)
Fortune Creek near the mouth (PET03)	Test	2012, 2013, 2014 (EC)
Petitot River downstream of Tsea River (PET07)	Test	2012, 2013, 2014 (EC)
Emile Creek near the mouth (EML01)	Test	2012, 2013, 2014 (EC)
Thetlaandoa Creek (THET01)	Test	2012, 2013 (EC)

C2.2 MODEL DEVELOPMENT

Classification of benthic communities

Results of the cluster analysis showed evidence of biological structure within the 53 reference sites sampled (Figure C3). Overall, 8 significantly different clusters were identified by the SIMPROF analysis in PRIMER; 3 of those clusters had only 1 or 2 sites and showed little similarity to the other 49 sites and limited similarity to each other and as such were considered outliers. Of the remaining 5 significantly different clusters, only 1 cluster met the minimum group size of 10 sites to ensure adequate variation was captured (Reynoldson et al. 2001). The small cluster of 6 sites on the far right of the dendrogram was rolled up with next most similar group to form Group 3 (symbol: triangle), consisting of 29 sites. Two small clusters of 5 sites and 9 sites in the middle of the dendrogram were combined to form Group 2 (symbol: diamond), consisting of 14 sites. Group 1 remained a small group of six sites (symbol: square); it was not rolled up with Group 2 because its similarity to the other reference sites was low, which highlighted a gap in this bioassessment model. More reference sites should be sampled to ensure that adequate variation of benthic communities similar to Group 1 is captured.

The average similarity among sites within each group was 40.77% in Group 1 (n=6), 42.46% in Group 2 (n=14) and 35.53% in Group 3 (n=29) where the dissimilarities between groups are distinguished by different proportions of similar taxa (Table C7). Group 3 was distinguished from Group 1 and Group 2 primarily by abundance and richness (Figure C4, Table C8), and Group 3 sites tended to have higher total abundances (Figure C5). Group 1 sites had the greatest proportions of stoneflies and caddisflies, while also having the highest diversity and evenness (Figure C6). Group 2 sites were similar in composition to Group 3 but had a much lower abundance (Figure C6). Group 2 was distinguished from Group 1 by a higher proportion of mayflies (Ephemeroptera, particularly Baetidae) and lower proportion of stoneflies

(Plecoptera) and caddisflies (Trichoptera, Figure C5; Table C8). Select community metrics are listed in Table C8 with detailed table in Appendix C (Table C2).

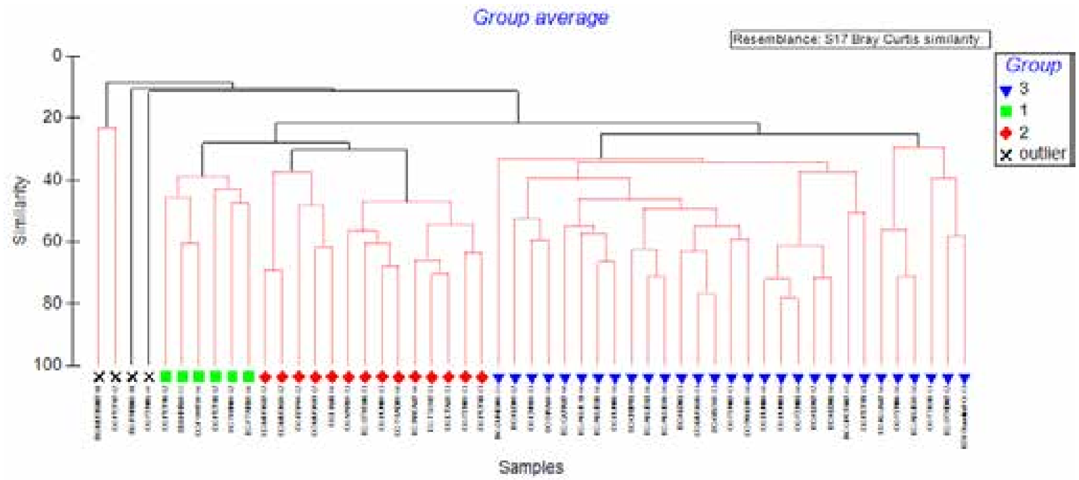


FIGURE C3. *Hierarchical group average cluster analysis of 53 reference sites in PRIMER6 using Bray-Curtis association. Sites connected by red lines could not be significantly differentiated by the SIMPROF procedure.*

TABLE C7. *SIMPER results of the top six contributing family level taxa to the differences between pairs of reference group communities.*

	GROUP 1		GROUP 2	
GROUP 2	Average dissimilarity = 71.87%			
	Capniidae	15.27		
	Hydropsychidae	13.26		
	Baetidae	9.21		
	Nemouridae	7.86		
	Chironomidae	6.69		
	Brachycentridae	6.40		
GROUP 3	Average dissimilarity = 77.95%		Average dissimilarity = 78.82%	
	Baetidae	14.13	Heptageniidae	15.44
	Heptageniidae	13.93	Chironomidae	14.75
	Chironomidae	12.17	Baetidae	14.62
	Nemouridae	10.20	Nemouridae	12.02
	Simuliidae	10.05	Simuliidae	11.05
	Capniidae	6.23	Hydropsychidae	5.19

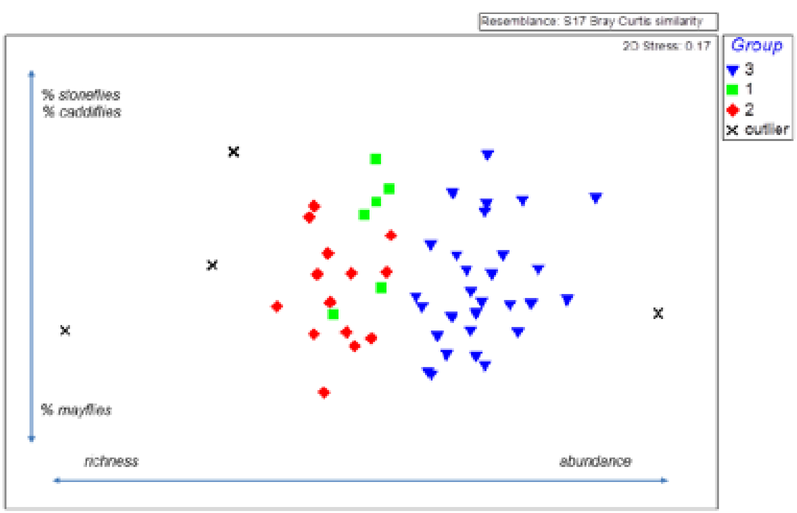


FIGURE C4. *Multidimensional scaling ordination of 53 reference site assemblages based on Bray-Curtis similarity of family level taxa with associated grouping and biological description.*

TABLE C8. *Descriptive metrics for the community assemblages of each reference group.*

COMMUNITY	GROUP 1 (N=6)		GROUP 2 (N=14)		GROUP 3 (N=29)	
METRIC	MEAN ± SD	(RANGE)	MEAN ± SD	(RANGE)	MEAN ± SD	(RANGE)
Abundance	**823.5±241.3**	**(488-1167.8)**	**421.3±172.5**	**(200-815.3)**	**2563.3±1249.4**	**(1073.3-5283.2)**
Richness	**21.8 ± 2.9**	**(17-25)**	**19.8 ± 5.5**	**(6-29)**	**17.3 ± 3.8**	**(10-28)**
Diversity	**0.85±0.05**	**(0.73-0.88)**	**0.76±0.10**	**(0.45-0.88)**	**0.75±0.10**	**(0.51-0.89)**
Evenness	**0.75±0.05**	**(0.67-0.81)**	**0.65±0.08**	**(0.45-0.76)**	**0.66±0.10**	**(0.48-0.83)**
% EPT*	**62 ± 15**	**(42-76%)**	**65 ± 14**	**(42-86%)**	**63 ± 22**	**(15-93%)**
% Ephemeroptera	**9 ± 7**	**(3-21%)**	**37 ± 21**	**(9-70%)**	**36 ± 22**	**(0-75%)**
% Plecoptera	**23 ± 21**	**(5-57%)**	**21 ± 21**	**(0-66%)**	**18 ± 19**	**(1-74%)**
% Trichoptera	**29 ± 12**	**(10-43%)**	**7 ± 5**	**(2-20%)**	**10 ± 9**	**(0-31%)**

*EPT = Ephemeroptera (mayflies), Plecoptera (stoneflies), Trichoptera (caddisflies)

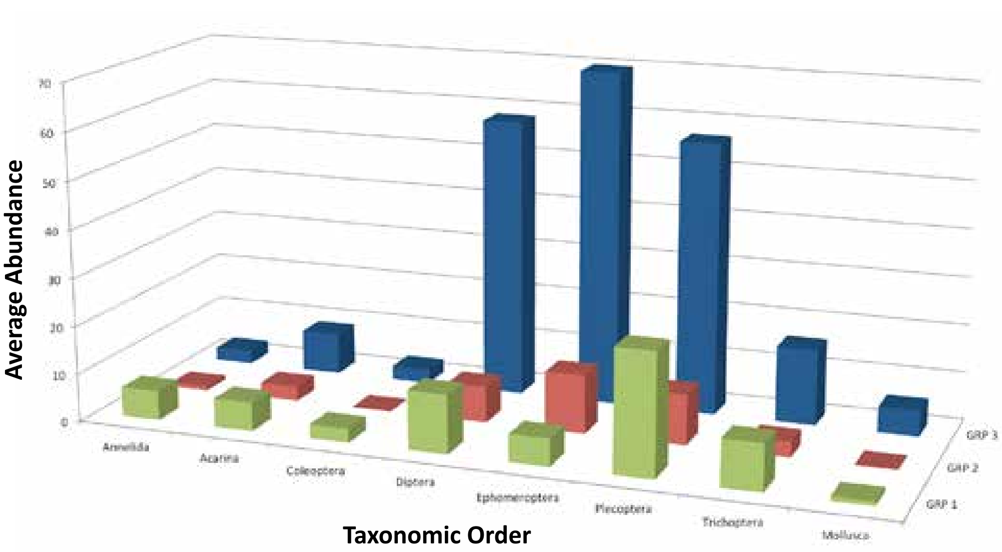


FIGURE C5. *Summary of the average abundance of the major taxa within each reference group.*

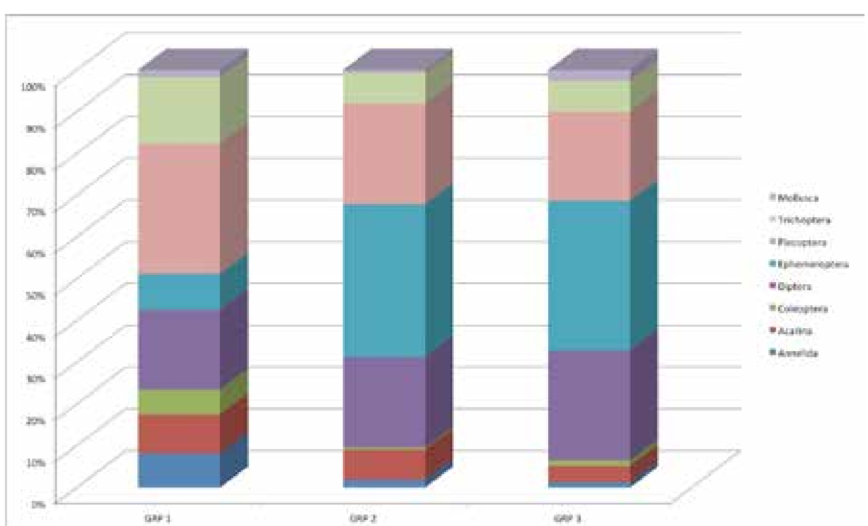


FIGURE C6. *Summary of the composition of the major taxa within each reference group.*

Selected environmental characteristics were summarized for each reference group (Table C9) with detailed results in Appendix C (Appendix Table C3). Group 2 sites tended to have deep channels, large substrates and faster velocities. Group 1 and Group 3 sites tended to be shallow with small substrates. Group 1 is distinguished from the other groups by its smaller watershed size, its drier, colder climate and its shallower topography. Group 3 sites tend have till blanket and less organic surficial geology, higher watershed elevations and a wetter climate with cool spring temperatures. The reference groups were not geographically distinct (Figure C7) and sites from all reference groups were distributed throughout the study area.

TABLE C9. *Select environmental characteristics of the three reference groups; predictor variables are shown in **bold**.*

STATISTICS	GROUP 1 (N=6)		GROUP 2 (N-14)		GROUP 3 (N=29)	
	MEDIAN	RANGE	MEDIAN	RANGE	MEDIAN	RANGE
Drainage Area (km^2)	92.1	25.0-8354.4	156.9	27.3-8354.4	125.1	16.7-8354.4
Channel Depth, avg (cm)	**8.7**	**5.60-24.00**	**22.75**	**10.00-72.20**	**13.4**	**6.70-38.50**
Channel Velocity, avg (m/s)	0.36	0.23-0.51	0.45	0.26-0.84	0.5	0.2-0.97
Substrate diameter, D50 (cm)	7	0.8-13.3	7.7	1.0-23.55	5.3	1.45-15.95
Precipitation, January (mm)	**20.3**	**18-22**	**24.2**	**21-27**	**25**	**19-28**
Temperature, May Min (°C)	**2**	**1.1-2**	**1.45**	**0.3-2**	**1**	**0-2**
Surficial Geology – Organic (%)	**0**	**0-48.59**	**4.2**	**0-100**	**0**	**0-46.55**
Elevation, avg (m)	519.5	469.4-619.7	618.5	435.5-990.6	678	467.1-1238.5
Slope, max (%)	**56**	**18-88**	**144.9**	**37.5-194.9**	**131**	**38.3-248.1**

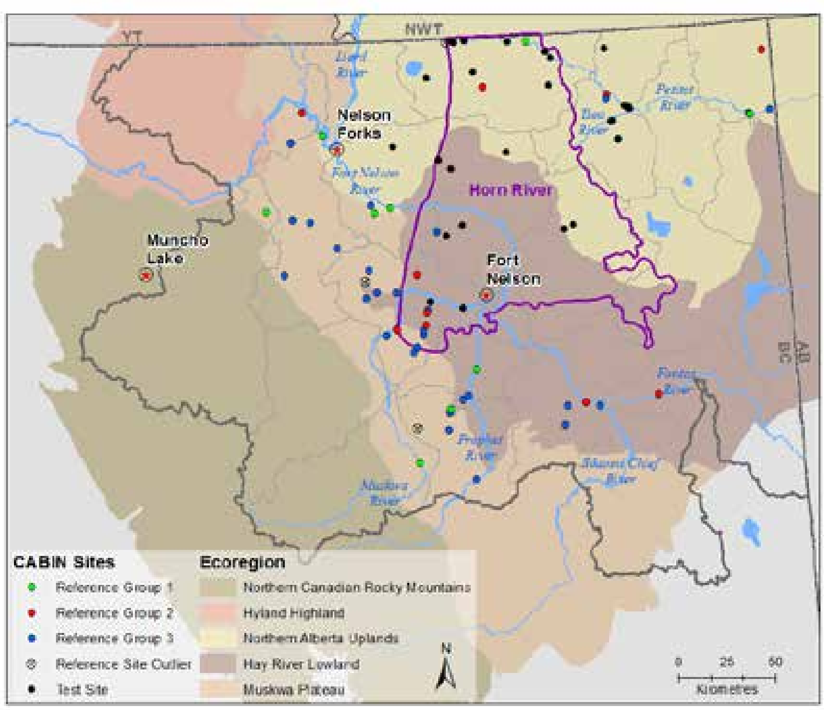


FIGURE C7. *CABIN sampling locations with the study area, ecoregions, and major sub-basins. Sites are identified as reference or test with associated preliminary model reference group. The underlying Horn River Basin is identified by the purple outline, indicating potential footprint of UOG activity.*

Establishing a predictive relationship with environmental characteristics

To predict the invertebrate community that should be observed in the absence of environmental stress, the range of environmental predictor variables should be distilled to those not affected by the stressor that is being assessed (Reynoldson et al. 1995). Recently, landscape-level GIS-derived variables have proven useful predictors of benthic communities alongside field collected habitat information (Townsend et al. 2003, Allan 2004, Waite et al. 2010, Armanini et al. 2012, Ligeiro et al. 2013). Approximately 120 different environmental variables were measured at each sampling site or derived from geographical coordinates ranging from site specific channel and substrate measurements to upstream landcover, underlying geology and 30 year climate averages.

A correlation analysis reduced the list of candidate predictor variables to 51 that were least correlated with each other (Table C10). It was important to have representation from each group of predictor variables. The range of correlations differed with each group of variables; for example, climate variables were the most highly correlated. As a result, climate variables that had the least number of correlations exceeding 0.8 were retained, reducing that group of variables from 39 to 18 possible predictors (Table C10). For the other groups of predictors, correlations were less prominent, so generally variables that had correlations exceeding 0.6 were excluded. The final set of habitat variables from the stepwise DFA and iterative process is shown in Table C11. Cross-validation and resubstitution rates, and their associated error rates, are summarized in Table C12.

The overall cross-validation error rate of this preliminary model (27%) was very good in comparison to other CABIN RCA models in Western Canada (www.ec.gc.ca/rcba-cabin): the cross validation rate for the Yukon 2013 model was 52%, the Fraser Basin 2014 was 49%, and the BC Central/North Coast 2015 was 33%. These models were built on much larger datasets (~300 sites) from a larger geographical area and likely captured more environmental variation. Although this northeast BC model was preliminary due to it having a smaller number of sites than recommended and with identified data gaps, we believe that the predictive ability of the model is sufficiently good within the range of the defined study area.

TABLE C10. *Reduced list of potential predictor variables.*

LOCATION	CHANNEL/ SUBSTRATE	CLIMATE	LANDCOVER
Latitude	Depth, Avg (cm)	Precip JAN	Broadleaf, Dense
Longitude	Channel slope (m/m)	Precip MAR	Broadleaf, Sparse
Altitude	Velocity, max (m/s)	Precip MAY	Coniferous, Open
	Width, bankfull (m)	Precip NOV	Grassland
MORPHOMETRY	% Boulder	Precip DEC	Herb
Drainage area	% Cobble	Temp, MAR min	Mixedwood, Dense
Stream density	% Pebble	Temp, APR max	Mixedwood, Open
		Temp, APR min	Shrub, tall
TOPOGRAPHY		Temp, MAY max	Wetland, herb
Elevation, avg		Temp, MAY min	Wetland, shrub
Elevation, min	SURFICIAL GEOLOGY	Temp, JUN max	Wetland, treed
% Slope 30-50%	% Colluvial	Temp, JUN min	
% Slope >60%	% Fine grained	Temp, JUL max	
Slope, max %	% Organic	Temp, JUL min	
	% Till blanket	Temp, AUG max	
	% Till veneer	Temp, SEP max	
		Temp, OCT min	
		Temp, ANNUAL min	

TABLE C11. *Optimal preliminary model variables determined from stepwise and iterative DFA.*

PREDICTOR VARIABLES	GROUP 1 MEAN	GROUP 2 MEAN	GROUP 3 MEAN	F-TO-REMOVE	TOLERANCE
Organic surficial geology (%)	**15.856**	**14.692**	**4.515**	**4.28**	**0.707**
Max upstream slope (%)	**51.767**	**127.014**	**126.266**	**4.645**	**0.409**
Average Depth (cm)	**12.017**	**26.75**	**17.472**	**20.137**	**0.471**
Min temperature, May (°C)	**1.85**	**1.436**	**1.2**	**22.006**	**0.158**
Precipitation, January (mm)	**20.183**	**24.229**	**24.241**	**18.376**	**0.271**

TABLE C12. *DFA classification rates for the optimal preliminary model.*

	NUMBER OF SITES				
RESUBSTITUTION	PREDICTED TO GROUP 1	PREDICTED TO GROUP 2	PREDICTED TO GROUP 3	% CORRECT	% ERROR
Assigned Group 1	**5**	0	1	83	17
Assigned Group 2	0	**14**	0	100	0
Assigned Group 3	4	2	**23**	79	21
Total	9	16	24	**86**	**14**
CROSS-VALIDATION	PREDICTED TO GROUP 1	PREDICTED TO GROUP 2	PREDICTED TO GROUP 3	% CORRECT	% ERROR
Assigned Group 1	**5**	0	1	83	17
Assigned Group 2	0	**11**	3	79	21
Assigned Group 3	5	4	**20**	69	31
Total	10	15	24	**73**	**27**

C2.3 MODEL EVALUATION

Simulated data are commonly used to evaluate assessment approaches, although the approaches to simulating data differ (Bowman and Somers 2005, Cao and Hawkins 2005, Mazor et al. 2006, Downie 2011, Bailey et al. 2012, Bailey et al. 2014). In some cases, known pollution tolerance scores (Hilsenhoff 1988, Barbour et al. 1999) are used to simulate communities based on which taxa are expected to increase or decrease (Downie 2011, Nichols et al. 2014, Strachan and Reynoldson 2014). These generic pollution tolerance scores are related to tolerance to oxygen depletion and reflect eutrophication impacts from organic pollution (Hilsenhoff 1988); they do not account for impacts from sedimentation, habitat degradation or water quantity expected to be associated with oil and gas activities (Hintz and Steffy 2015). The RDT (resource development tolerance) was developed specific to sedimentation and fining of substrates to reflect taxa tolerance to potential changes in the stream caused by increased erosion from construction and use of transportation and pipeline corridors. Sixteen taxa were designated "sensitive" (RDT below -0.65) and eleven taxa designated "tolerant" (RDT above 0.65) to resource development (Table C13).

Figure C8 illustrates the results of simulated disturbance of resource development at three different intensities on the reference group assemblages. Overall, the simulated disturbance had a more pronounced effect on richness than abundance. The effect on abundance was more pronounced for Group 3 communities (Figure C8a). In all communities, the simulation decreases abundance slightly on sensitive organisms but then increases due to the increase in tolerant organisms. The simulation for richness is similar for all three reference groups (Figure C8b). At the first level of disturbance, the overall average community abundance decreased slightly and the total richness was unchanged. Between the first and second intensity levels, however, the total richness decreased dramatically. However, the abundance response differed for each reference group; Group 1 showed a slight increase, Group 3 showed an obvious increase and Group 2 showed a slight decrease. At the highest level of simulated disturbance, richness continued to decrease in all reference groups and the abundance increased for all groups but at different rates.

TABLE C13. *Taxa designated "Sensitive" and "Tolerant" by the RDT, and used for simulating resource development disturbance to reference communities.*

TAXA DESIGNATED "SENSITIVE"	TOLERANCE	TAXA DESIGNATED "TOLERANT"	TOLERANCE
Uenoidae	-0.89	Tubificidae	1.0
Ameletidae	-0.78	Gammaridae	0.89
Apataniidae	-0.78	Corixidae	0.78
Hydryphantidae	-0.78	Hyalellidae	0.78
Lepidostomatidae	-0.78	Muscidae	0.78
Perlidae	-0.78	Pisidiidae	0.78
Piscicolidae	-0.78	Sialidae	0.78
Planariidae	-0.78	Haliplidae	0.67
Rhyacophylidae	-0.78	Perlodidae	0.67
Baetidae	-0.67	Pteronarcyidae	0.67
Ephemerellidae	-0.67	Tipulidae	0.67
Hydrozetidae	-0.67		
Leuctridae	-0.67		
Nemouridae	-0.67		
Oreoleptidae	-0.67		
Torrenticolidae	-0.67		

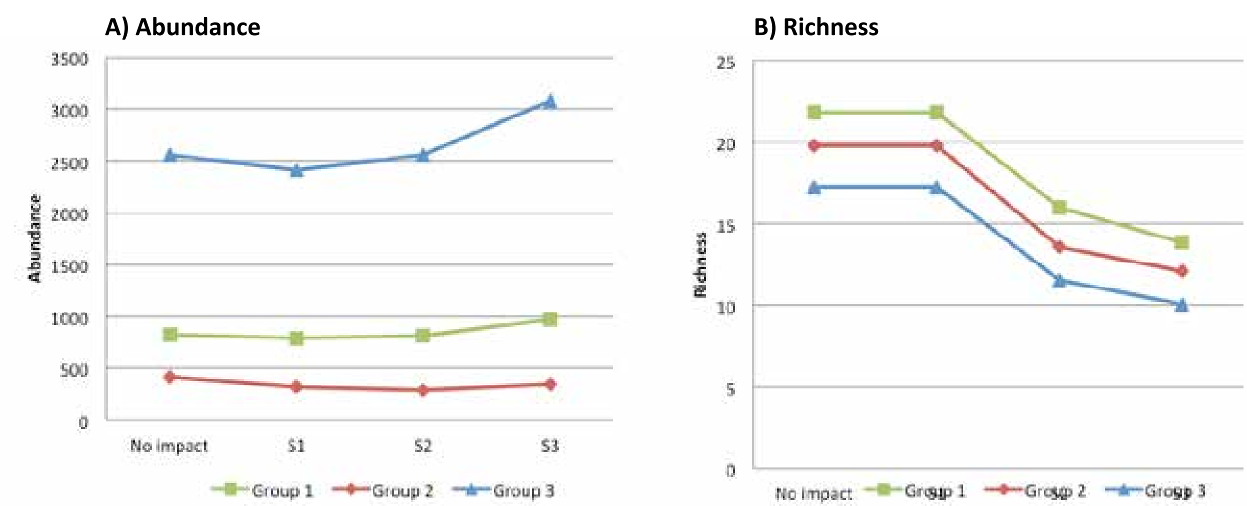


FIGURE C8. *The change in average abundance (A) and average family richness (B) for the three groups of reference communities in response to three levels of simulated resource development disturbance (S1, S2, S3).*

The simulated disturbance intensities may not reflect real world conditions; however the most important aspect of this evaluation was that the reference data were predictably altered by different factors according to known correlations of local taxa with environmental conditions. If the model performance increased as the simulated disturbance intensity increased, then the model was working well.

Model performance was assessed by examining the Type 1 and Type 2 error rates associated with the simulated data at all three intensity levels, with the preferred model providing a balance of Type 1 and Type 2 error rates. Typically, a low Type 1 error rate (mistakenly determining a reference site is impaired) often means that the Type 2 error rate (not detecting impairment at a site that is affected by disturbance) will be high. Figure C9 illustrates the results

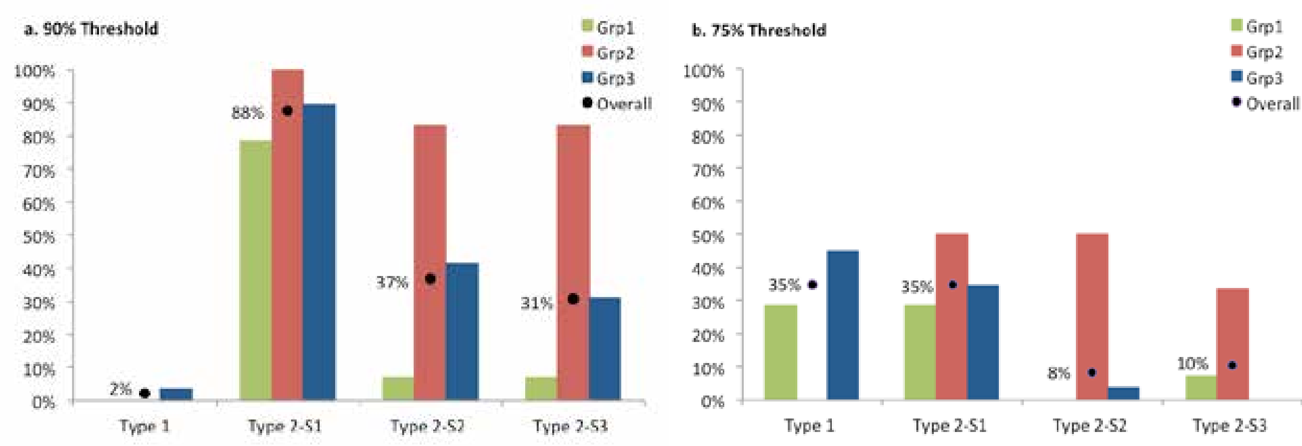


FIGURE C9. *Type 1 and Type 2 error rates for each reference group and the overall model with three levels of simulated intensities (S1, S2, S3) of resource development disturbance using a 90% confidence ellipse (a) and a 75% confidence ellipse (b) as divergence thresholds.*

of the resource development simulated disturbance at three different intensities using two different divergence thresholds for the 49 reference sites used to develop the model.

The standard assessment thresholds for a CABIN analysis use a 90% ellipse for the first threshold for detecting divergence from the expected reference condition. At a 90% threshold, the overall Type 1 error rate was very low and the overall Type 2 error rate was very high (Figure C9a). Using a 75% threshold for the simulated resource development disturbance, Type 2 error rates decreased from 88% to 35% for S1 and from 31% to 10% for S3 (Figure C9b), and were more balanced with Type 1 error.

In the interest of environmental protection and to have a balance of Type 1 and Type 2 errors, a 75% threshold as the first indication of divergence from expected condition is recommended for this preliminary bioassessment model. Furthermore, revising the standard CABIN ellipses to 75%, 90% and 95% for distinguishing levels of divergence with this preliminary model is recommended (Figure C10). This model was based on data from 49 reference sites with two small groups of 6 sites and 14 sites; therefore, it is likely that as more reference data become available to better describe the natural variation of northeast BC, the standard CABIN ellipses (90%, 99%, 99.9%) could be used in revisions of this model to describe degrees of deviation from reference condition.

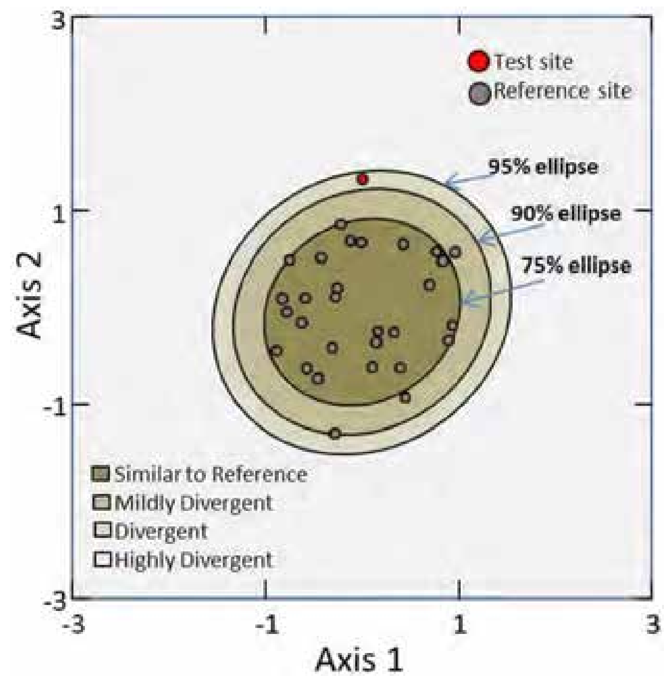


FIGURE C10. *Proposed CABIN assessment ellipses for the preliminary model.*

C2.4 TEST SITE ASSESSMENT

There is an important and notable difference between biological monitoring and physical-chemical monitoring: physical-chemical monitoring provides a quantitative measure of particular variables at the time of sampling, whereas biological monitoring provides a measure of the cumulative effects occurring in the watershed over the course of the life of the aquatic biota. Biomonitoring can provide an early warning of missed or unmeasured effects to water quality over time, or of disturbances which cannot be measured by physical-chemical monitoring such as habitat degradation. Together, biomonitoring and physical-chemical monitoring enhance our understanding of ecosystem health.

Two thirds of the test sites analysed (22/33) were outside of the 90% threshold, suggesting that the benthic communities from areas exposed to UOG activity were different than the reference communities (Table C14). For comparison, assessment results of the degree of deviation from reference for both the standard CABIN thresholds (90%, 99%, 99.9%) and the proposed thresholds for this model (75%, 90%, 95%) are presented in this report.

Correlations among the assessment results based on the proposed ellipses (Figure C10) and year specific geospatial stressor information for well type (i.e. active , suspended, cased, abandoned, etc.), waste disposal and facility information, roads, pipelines, stream crossings, changes near the stream, and water use licenses were examined. Degree of divergence of the benthic communities in northeast BC was not correlated with any of the stressor variables available in the BCOGC geospatial data layers. A similar baseline study of the Marcellus Shale, PA for the Susquehanna River Basin found no correlation between macroinvertebrate integrity indicators and well density or number of wells near the sampling site (Hintz and Steffy 2015). However, another study found positive correlations between Ephemeroptera, Plecoptera and Trichoptera (EPT) taxa and inverse flow path length (IFPL) and well density in stream catchments in the Fayetteville Shale, AR (Johnson et al. 2015b).

Water quality variables measured at test sites were compared to those of the predicted range of reference sites (i.e. range of expected reference condition water quality concentrations). Generally variables measured at most test sites were within the 99th percentile. At three sites, Ba concentrations were outside the range of those found in the predicted reference group. While Ba may be an indicator of UOG activity or resource development, the measured concentrations were relatively low (53-58 µg/L) and were not correlated with the benthic community degree of divergence from reference condition.

Despite a lack of correlation with geospatial stressor variables, the reference communities were different than expected, suggesting that there is something impacting the benthic macroinvertebrate communities. The study area in northeast BC is remote with low UOG activity in comparison to activities occurring elsewhere in North America (Section 1, Table 1). In basins around the Fayetteville Shale (AR), Johnson et al. (2015a) reported that benthic communities reflected a disturbance gradient of UOG activity. This study also found that >60% of the test sites exposed to UOG activity in northeast BC could be considered impaired (i.e. outside 90% threshold). These are in contrast to results reported by Hintz and Steffy (2015) where only 6% of exposed sites showed impairment in the development area of the Susquehanna River Basins (Pennsylvania). The starting condition of the aquatic ecosystem for these three studies in different areas of development, as well as the intensity of UOG activities in each of the areas, may play a role in these conflicting responses.

Test sites in northeast BC that were sampled in multiple years to investigate the effect of temporal variation were predicted to different groups due to annual fluctuations in hydrology. Using the Hay River as an indicator of regional hydrology (Figure C11) the following observations can be made: In 2012 the spring discharge was the lowest it had been since 2004 and also the lowest average discharge in the month of August since 2004; and in 2013 the spring discharge was the highest it had been since 2009 although the average August discharge in 2013 and 2014 was typical.

Not only do these extreme hydrological fluctuations represent an important environmental stress for aquatic biota, the change in hydrology from year to year affected where revisited sites could be accessed via helicopter and where sampling was conducted. Although the same overall location on the Petitot River was sampled at the same time of year between 2012 and 2014, the location within the river was different due to flow conditions. CABIN methodology requires macroinvertebrates to be sampled in a riffle/run habitat; during low water, sampling is typically conducted further toward the middle of the river, away from stagnant littoral zones, whereas during high water, sampling is limited to the wadeable littoral zones. The expected community composition for different flow conditions will change, with a corresponding change in the model prediction and the baseline against which the community is compared. Average depth was the only field-measured predictor variable in this model which took into account annual variability in flow while the other landscape predictor variables were unchanged (Table C15).

TABLE C14. *Test sites with model prediction results (predicted group and probability of group membership) and ordination assessment results using standard CABIN thresholds and proposed assessment thresholds for this preliminary model (band 1=similar to reference, band 2=mildly divergent, band 3 = divergent, band 4 = highly divergent).*

	MODEL PREDICTIONS				ASSESSMENT BAND RESULTS		
SITE	PREDICTED GROUP	PROB 1	PROB 2	PROB 3	ORDINATION STRESS	STANDARD THRESHOLDS	PROPOSED THRESHOLDS
FNR001-10	2	0%	100%	0%	0.1594	2	4
LFRT002-11	2	0%	76%	24%	0.1359	2	4
LFRT003-11	2	1%	77%	22%	0.1599	2	4
LFRT005-11	1	59%	0%	40%	0.1132	1	2
LPET004-11	2	0%	100%	0%	0.1533	2	4
MUSK001-10	2	0%	100%	0%	0.1488	2	4
CAP02-13	2	0%	92%	8%	0.1502	2	3
CVR01-12	1	100%	0%	0%	0.1202	2	3
CVR02-14	1	99%	0%	1%	0.1183	2	3
DIL01-12	1	84%	0%	16%	0.1117	1	2
EML01-12	3	17%	8%	75%	0.1911	1	2
EML01-13	2	2%	55%	43%	0.146	1	1
EML01-14	2	0%	81%	18%	0.1541	2	4
EML02-12	3	29%	3%	68%	0.1895	2	3
HOS01-13	1	96%	0%	4%	0.1092	1	2
MUSK04-12	2	1%	85%	14%	0.1407	2	3
PET01-12	2	0%	95%	5%	0.1321	2	4
PET01-13	1	86%	0%	14%	0.113	1	2
PET01-14	3	12%	20%	69%	0.1888	1	2
PET03-12	3	38%	11%	52%	0.1917	2	3
PET03-13	2	1%	89%	10%	0.1535	2	4
PET03-14	3	30%	16%	54%	0.1923	1	2
PET04-12	1	70%	0%	30%	0.1114	1	2
PET05-12	1	90%	0%	10%	0.1047	2	3
PET07-12	3	49%	1%	50%	0.1964	2	3
PET07-13	2	0%	86%	13%	0.1499	2	4
PET07-14	3	11%	16%	74%	0.1902	2	3
STND01-12	3	5%	37%	57%	0.1914	2	3
THET01-12	1	98%	0%	2%	0.1252	2	4
THET01-13	3	18%	35%	48%	0.1875	1	1
TSEA001-12	1	82%	0%	18%	0.0955	1	1
TSEA002-12	1	99%	0%	1%	0.1219	2	3
Stanolind-12	2	3%	50%	47%	0.1355	2	4

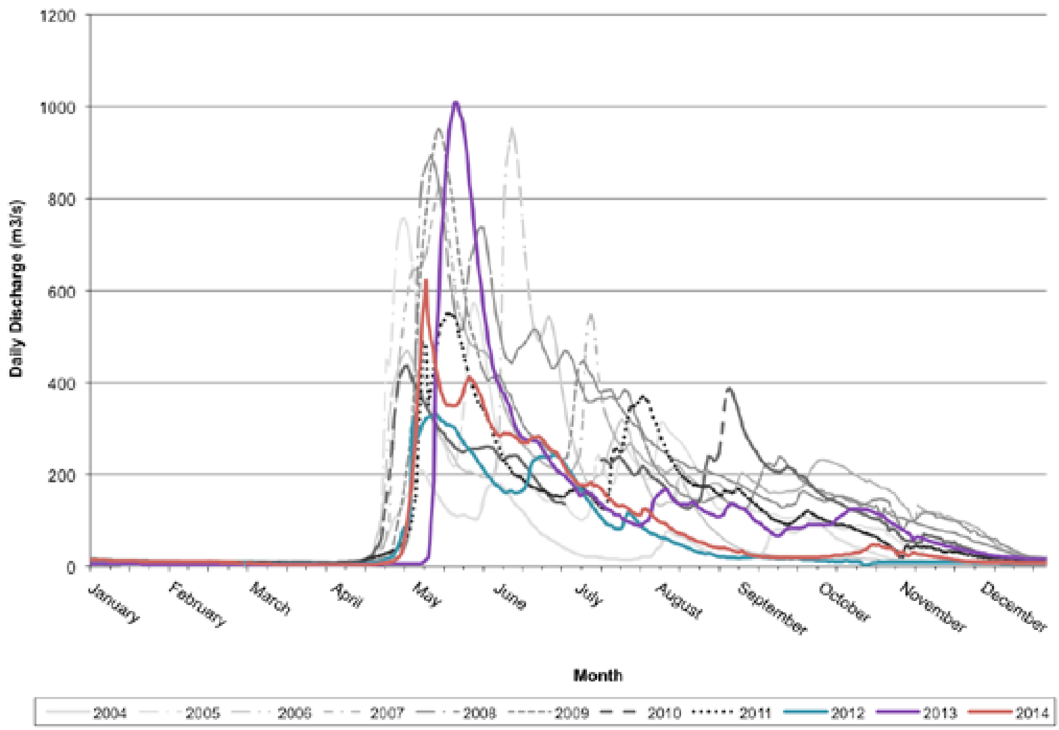


FIGURE C11. *Representative hydrograph of the Hay River (WSC station 07OB001) for a 10 year period illustrating the hydrology fluctuations in the years leading up to this study and during the study period. Data from Water Survey of Canada.*

TABLE C15. *Predictor variables of test sites sampled in multiple years and the result on the predicted group used for assessment.*

SITE	YEAR	PREDICTED GROUP	AVERAGE DEPTH (FIELD)	CLIMATE-PRECIP JAN	CLIMATE-TEMP MAY MIN	SURFICIAL GEOLOGY ORGANIC %	TOPOGRAPHY-SLOPE, MAX %
EML01	2012	3	8.5	22.3	2	0.00	65
EML01	2013	2	18.1	22.3	2	0.00	65
EML01	2014	2	23	22.3	2	0.00	65
PET01	2012	2	55.8	20.8	1.5	0.00	83
PET01	2013	1	19.2	20.8	1.5	0.00	83
PET01	2014	3	39.5	20.8	1.5	0.00	83
PET03	2012	3	8.7	21.8	2	13.29	74.2
PET03	2013	2	23.2	21.8	2	13.29	74.2
PET03	2014	3	10.2	21.8	2	13.29	74.2
PET07	2012	3	35	20.7	1.4	0.00	65
PET07	2013	2	59	20.7	1.4	0.00	65
PET07	2014	3	45.7	20.7	1.4	0.00	65
THET01	2012	1	19.2	19.3	1.8	0.00	41.2
THET01	2013	3	45.7	19.3	1.8	0.00	41.2

Channel depth is a potential source of disturbance from water withdrawals for hydraulic fracturing activities, however the reported withdrawals as a percentage of mean annual runoff in the Horn River Basin for 2013 and 2014 were less than 0.04% except for the Tsea River Basin which was 0.24% in 2014 (BCOGC 2013b, 2014, 2015d). In 2012, the BCOGC suspended short-term water withdrawals in August November due to drought conditions (BCOGC 2013b). The landscape level climate variables included in the predictive model would not accurately reflect the extreme hydrological conditions experienced over the three years of this study. Flow conditions greatly influence the benthic macroinvertebrate community and a representative variable was needed to match a reference community in normal versus drought conditions, therefore channel depth was included as a predictive variable. Of the test sites examined in this study, the potential influence of UOG activity on channel depth would likely be a concern on one site (PET07) in the Tsea River watershed resulting in an overestimate of the condition of the community.

The BCOGC reported very low water withdrawals in the Horn River Basin in 2015 although sampling did not occur in this year (BCOGC 2016). If this continues, the use of depth as a predictor variable should not be a concern. However, other field-measured predictors that are not sensitive to water withdrawals should be explored to replace the water depth measurement in this preliminary model. The effects of climate related hydrology fluctuations versus the effects of UOG activity should be further investigated by continuing biomonitoring at a subset of test sites as well as a proportion of reference sites. Other studies have reported difficulties in separating the effects of hydrology on macroinvertebrates from the effects of UOG activity (Hintz and Steffy 2015, Johnson et al. 2015b), reinforcing the importance of regular biological and hydrological monitoring. Additionally, other components of this study related to water quality did not detect strong effects from UOG activity (*see sections A3 and B3*).

C3. CONCLUSIONS AND RECOMMENDATIONS

- The baseline information and preliminary model will be available through the CABIN website for future assessment of aquatic ecosystem health in northeast BC. CABIN training is available for anyone interested in using the model or the shared reference data.
- Nearly two thirds of all the sites exposed to UOG activity fell outside of the 90% threshold, suggesting that the biological community is different than expected. However, the differences were not correlated with any of the BCOGC geospatial stressor variables. In addition, most water quality variables at most test sites were within the range of those measured at reference sites. Further assessment is required to determine the cause of divergence, but it is possible that climate related hydrological fluctuations may have provided a confounding effect on the stream ecosystems during the short duration of this study.
- Unlike other areas of UOG activity in North America, northeast BC is remote and the level of other human related disturbances is still relatively low. Therefore, this study provides a baseline of aquatic ecosystem health conditions. Continued monitoring will be able to provide information related to the effects of UOG activity.
- Temporal monitoring is critical over the long-term to better understand effects from interannual variability in hydrological conditions versus oil and gas influences.
- Baseline information will contribute to an improved understanding of regional ecosystem health in the Petitot, Fort Nelson and Hay River basins. Knowledge generated as part of this project will inform the design of expanded monitoring in the area and in other shale gas plays, and support resource management decisions.

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APPENDIX A

APPENDIX TABLE A1. *Analytical methods by variable for grab samples.*
*Acronyms are CRC-ICP-MS: Inductively Coupled Argon Plasma-Collision/Reaction Cell Mass Spectrometry; ICP-OES: ICP-OES: Inductively Coupled Plasma Optical Emission Spectrometry; ICP-AES: Inductively Coupled Plasma Atomic Emission Spectrometry. Hardness calculation: Total Hardness = 2.497248*Ca + 4.116885*Mg.*

VARIABLE	VARIABLE NAME	UNITS	MDL	ANALYTICAL METHOD	LABORATORY
Alk.tot	Alkalinity, Total	mg $CaCO_3$/L	0.5	Potentiometric Titration	PYLET/Maxxam
Al.tot	Aluminum, Total Recoverable	µg/L	0.5	CRC-ICP-MS	NLET
As.tot	Arsenic, Total Recoverable	µg/L	0.01	CRC-ICP-MS	NLET
Ba.tot	Barium, Total Recoverable	µg/L	0.05	CRC-ICP-MS	NLET
Be.tot	Beryllium, Total Recoverable	µg/L	0.001	CRC-ICP-MS	NLET
B.tot	Boron, Total Recoverable	µg/L	0.5	CRC-ICP-MS	NLET
Cd.tot	Cadmium, Total Recoverable	µg/L	0.001	CRC-ICP-MS	NLET
Ca.diss.ext	Calcium, Dissolved / Extractable	mg/L	0.1 0.05	ICP-OES ICP-AES	PYLET Maxxam
DIC	Carbon, Dissolved Inorganic	mg/L	0.5	Infrared Combustion Colorimetric	PYLET Maxxam
DOC	Carbon, Dissolved Organic	mg/L	0.5	Infrared Combustion Colorimetric	PYLET Maxxam
Cl.diss	Chloride, Dissolved	mg/L	0.1 0.5	Ion Chromatography (ICA) Colorimetric	PYLET Maxxam
Cr.tot	Chromium, Total Recoverable	µg/L	0.01	CRC-ICP-MS	NLET
Co.tot	Cobalt, Total Recoverable	µg/L	0.002	CRC-ICP-MS	NLET
Cu.tot	Copper, Total Recoverable	µg/L	0.02	CRC-ICP-MS	NLET
Hardness	Hardness, Total Dissolved (calc)	mg $CaCO_3$/L	0.4 0.5	Calculation* Calculation*	PYLET Maxxam
Fe.tot	Iron, Total Recoverable	µg/L	0.5	CRC-ICP-MS	NLET
Pb.tot	Lead, Total Recoverable	µg/L	0.005	CRC-ICP-MS	NLET
Li.tot	Lithium, Total Recoverable	µg/L	0.01	CRC-ICP-MS	NLET
Mg.diss.ext	Magnesium, Dissolved / Extractable	mg/L	0.1 0.05	ICP-OES ICP-AES	PYLET Maxxam
Mn.tot	Manganese, Total Recoverable	µg/L	0.05	CRC-ICP-MS	NLET

APPENDIX TABLE A1. *Con't.*

VARIABLE	VARIABLE NAME	UNITS	MDL	ANALYTICAL METHOD	LABORATORY
Mo.tot	Molybdenum, Total Recoverable	µg/L	0.005	CRC-ICP-MS	NLET
NO_3	Nitrogen, Nitrate as N	mg/L	0.005	Ion Chromatography (ICA) Calculated	PYLET
			0.002		Maxxam
NO_2	Nitrogen, Nitrite as N	mg/L	0.005	Ion Chromatography (ICA) Colorimetric	PYLET
			0.002		Maxxam
pH	pH	pH units	0.01	pH Meter/Low Ionic Strength	PYLET/Maxxam
K.diss.ext	Potassium, Dissolved / Extractable	mg/L	0.1	ICP-OES ICP-AES	PYLET
			0.05		Maxxam
TSS	Solids, Total Suspended	mg/L	2	Gravimetric	PYLET
			1		Maxxam
Rb.tot	Rubidium, Total Recoverable	µg/L	0.001	CRC-ICP-MS	NLET
Na.diss.ext	Sodium, Dissolved / Extractable	mg/L	0.1	ICP-OES ICP-AES	PYLET
			0.05		Maxxam
Sp.cond	Conductance, Specific	µS/cm	2	Conductivity Meter (corrected to 25 C)	PYLET
			1		Maxxam
Sr.tot	Strontium, Total Recoverable	µg/L	0.05	CRC-ICP-MS	NLET
SO_4	Sulphate, Dissolved	mg/L	0.5	Ion Chromatography (ICA) Turbimetric	PYLET
					Maxxam
U.tot	Uranium, Total Recoverable	µg/L	0.0005	CRC-ICP-MS	NLET
V.tot	Vanadium, Total Recoverable	µg/L	0.005	CRC-ICP-MS	NLET
Zn.tot	Zinc, Total Recoverable	µg/L	0.2	CRC-ICP-MS	NLET

APPENDIX TABLE A2. *Properties of conductivity loggers installed during the study.*

	HOBO	SOLINST
Sensor	Non-contact titanium	4 electrode platinum
Calibrated Measurement range (conductivity)	Low range: 0-1000 µS/cm High range: 0-10000 µS/cm	500 to 50000 µS/cm (operating range 0-80000 µS/cm)
Calibrated measurement range (temperature)	5 to 35 deg C	n/a
Specific conductance accuracy	Low range: 3% of reading or 5 µS/cm High range: 3% of reading or 20 µS/cm	2% of reading or 20 µS/cm
Conductivity resolution	1 µS/cm	1 µS/cm
Temperature accuracy	0.1 deg C	0.1
Temperature resolution	0.01 deg C	0.1
Operating temperature range	-2 to 36 deg C – non freezing	-20 to 80 deg C
Calibration/Drift	Conducted within HOBOWARE. Start and end point calibration to account for fouling and drift.	Calibration required before deployment

APPENDIX TABLE A3. *The data completeness record (in percent) is shown by year for continuous conductivity data at five water quality stations and the average (avg) for the Petitot River Basin. August 2014 to July 2015 was the data record analysed in this report based on completeness. Days where there was greater than 80% completeness of the daily record were included. Cells are highlighted red where completeness was less than 50%. Yearly percentages are based on the number of months between the first month on record and the last month with data for each station.*

		EMILE	FORTUNE	PET77	PETTSEA	SAHD	PETITOT BASIN (AVG)
2013	May	0.0	0.0	67.7	0.0	71.0	27.7
	Jun	0.0	0.0	100.0	0.0	100.0	40.0
	Jul	67.7	67.7	100.0	67.7	100.0	80.6
	Aug	100.0	100.0	100.0	100.0	100.0	100.0
	Sep	100.0	100.0	100.0	100.0	100.0	100.0
	Oct	100.0	100.0	100.0	100.0	74.2	94.8
	Nov	100.0	100.0	96.7	100.0	0.0	79.3
	Dec	100.0	87.1	100.0	100.0	0.0	77.4
	2013 (avg)	**71.0**	**69.4**	**95.6**	**71.0**	**68.1**	**75.0**
2014	Jan	100.0	0.0	58.1	58.1	0.0	43.2
	Feb	100.0	0.0	0.0	0.0	0.0	20.0
	Mar	100.0	0.0	0.0	0.0	0.0	20.0
	Apr	100.0	0.0	0.0	0.0	0.0	20.0
	May	100.0	83.9	0.0	0.0	0.0	36.8
	Jun	100.0	100.0	0.0	0.0	0.0	40.0
	Jul	58.1	58.1	0.0	0.0	0.0	23.2
	Aug	61.3	54.8	64.5	0.0	0.0	36.1
	Sep	100.0	100.0	100.0	0.0	0.0	60.0
	Oct	80.6	96.8	93.5	0.0	71.0	68.4
	Nov	96.7	100.0	96.7	0.0	100.0	78.7
	Dec	100.0	100.0	100.0	0.0	100.0	80.0
	2014 (avg)	**91.4**	**57.8**	**42.7**	**4.8**	**22.6**	**43.9**
2015	Jan	100.0	100.0	100.0	0.0	100.0	80.0
	Feb	100.0	100.0	100.0	0.0	100.0	80.0
	Mar	100.0	100.0	100.0	0.0	100.0	80.0
	Apr	100.0	100.0	66.7	0.0	100.0	73.3
	May	100.0	100.0	0.0	0.0	100.0	60.0
	Jun	23.3	100.0	83.3	0.0	100.0	61.3
	Jul	0.0	35.5	38.7	0.0	38.7	22.6
	2015 (avg)	**74.8**	**90.8**	**69.8**	**0.0**	**91.2**	**65.3**
August 2014 - July 2015	Aug-2014	61.3	54.8	64.5	0.0	0.0	36.1
	Sep-2014	100.0	100.0	100.0	0.0	0.0	60.0
	Oct-2014	80.6	96.8	93.5	0.0	71.0	68.4
	Nov-2014	96.7	100.0	96.7	0.0	100.0	78.7
	Dec-2014	100.0	100.0	100.0	0.0	100.0	80.0
	Jan-2015	100.0	100.0	100.0	0.0	100.0	80.0
	Feb-2015	100.0	100.0	100.0	0.0	100.0	80.0
	Mar-2015	100.0	100.0	100.0	0.0	100.0	80.0
	Apr-2015	100.0	100.0	66.7	0.0	100.0	73.3
	May-2015	100.0	100.0	0.0	0.0	100.0	60.0
	Jun-2015	23.3	100.0	83.3	0.0	100.0	61.3
	Jul-2015	0.0	35.5	38.7	0.0	38.7	22.6
		80.2	**90.6**	**78.6**	**0.0**	**75.8**	**65.0**

APPENDIX TABLE A4. *The data completeness record (in percent) is shown by year for continuous water temperature data at five water quality stations and the average (avg) for Petitot River Basin. The entire dataset was used for time series plots and guidelines comparisons however; summary statistics were calculated using the most complete dataset August 2014 to July 2015. Days where there was greater than 80% completeness of the daily record were included. Cells are highlighted red where completeness was less than 50%. Yearly percentages are based on the number of months between the first month on record and the last month with data for each station.*

		EMILE	FORTUNE	PET77	PETTSEA	SAHD	PETITOT BASIN (AVG)
2013	May	0.0	0.0	67.7	0.0	71.0	27.7
	Jun	0.0	0.0	100.0	0.0	100.0	40.0
	Jul	67.7	67.7	100.0	67.7	100.0	80.6
	Aug	100.0	100.0	100.0	100.0	100.0	100.0
	Sep	100.0	100.0	100.0	100.0	100.0	100.0
	Oct	100.0	100.0	100.0	100.0	100.0	100.0
	Nov	100.0	100.0	100.0	100.0	100.0	100.0
	Dec	100.0	87.1	100.0	100.0	100.0	97.4
	2013 (avg)	**71.0**	**69.4**	**96.0**	**71.0**	**96.4**	**80.7**
2014	Jan	100.0	0.0	58.1	58.1	100.0	63.2
	Feb	100.0	0.0	0.0	0.0	100.0	40.0
	Mar	100.0	0.0	0.0	0.0	100.0	40.0
	Apr	100.0	0.0	0.0	0.0	100.0	40.0
	May	100.0	83.9	0.0	0.0	100.0	56.8
	Jun	100.0	100.0	0.0	0.0	100.0	60.0
	Jul	100.0	100.0	0.0	0.0	100.0	60.0
	Aug	100.0	100.0	64.5	64.5	100.0	85.8
	Sep	100.0	100.0	100.0	100.0	100.0	100.0
	Oct	100.0	100.0	100.0	100.0	100.0	100.0
	Nov	100.0	100.0	100.0	100.0	100.0	100.0
	Dec	100.0	100.0	100.0	100.0	100.0	100.0
	2014 (avg)	**100.0**	**65.3**	**43.5**	**43.5**	**100.0**	**70.5**
2015	Jan	100.0	100.0	100.0	100.0	100.0	100.0
	Feb	100.0	100.0	100.0	100.0	100.0	100.0
	Mar	100.0	100.0	100.0	100.0	100.0	100.0
	Apr	100.0	100.0	100.0	100.0	100.0	100.0
	May	100.0	100.0	100.0	100.0	100.0	100.0
	Jun	100.0	100.0	100.0	100.0	100.0	100.0
	Jul	29.0	38.7	38.7	38.7	38.7	36.8
	2015 (avg)	**89.9**	**91.2**	**91.2**	**91.2**	**91.2**	**91.0**

APPENDIX TABLE A5. *Range and median values compared to British Columbia approved water quality guidelines for the protection of aquatic life are shown for the water quality variables measured at each of the five routine monitoring study sites. Median values for the Petitot River Basin are also provided. Guideline exceedances are* ***bold****. Other guideline sources were used in the absence of a BC water quality guideline and are noted below.*

			FORTUNE N=12		EMILE N=12		SAHDOANAH N=12		PETITOT D/S TSEA N=13		PETITOT AT HIGHWAY 77 N=15		PETITOT RIVER BASIN
VARIABLE	GUIDELINE	UNITS	RANGE	MEDIAN	RANGE	MEDIAN	RANGE	MEDIAN	RANGE	MEDIAN	RANGE	MEDIAN	MEDIAN
Alk.tot	20***	mg/L	22.3 - 104	64.5	42.6 - 261	109.15	34.5 - 162	75.7	48.5 - 139	90.5	43 - 153	101	82
Al.tot	5000 (wildlife)	µg/L	20.7 - 2430	55.4	5 - 1620	33.65	27.5 - 775	75.9	18.2 - 298	41.6	16.9 - 1090	46.9	48.9
As.tot	5	µg/L	0.18 - 2.29	0.365	0.34 - 2.24	0.545	0.39 - 1.48	0.665	0.35 - 1.03	0.55	0.35 - 2.14	0.6	0.55
Ba.tot	1000†	µg/L	15 - 39.8	29.9	28.4 - 98.9	53.25	26.1 - 51.8	39.6	30.9 - 55.4	40.1	27.8 - 83.1	46.1	40.1
Be.tot		µg/L	0.006 - 0.166	0.0135	0.005 - 0.134	0.0085	0.008 - 0.078	0.0175	0.005 - 0.031	0.011	0.005 - 0.11	0.011	0.0125
B.tot	1200	µg/L	3.9 - 28.4	12.75	5.5 - 46.2	10.45	7.3 - 32.2	12.35	8.9 - 19.9	12.8	6.4 - 22.3	14.6	13.3
Br.tot[1]		µg/L	83% < DL	NC	<0.02 - 0.17	NC	< 0.02 - 0.07	0.03	67% < DL	NC	<0.01 - < 0.05	0.013	66% < DL
Cd.tot	0.069 – 0.40‡	µg/L	**0.005 - 0.075**	0.011	**0.013 - 0.214**	0.019	0.013 - 0.097	0.023	0.005 - 0.037	0.01	**0.006 - 0.163**	0.019	0.017
Ca.diss.ext		mg/L	11 - 41.5	24.3	19.1 - 90.3	41.2	18.7 - 62.7	33.9	22.4 - 48.2	34.4	19.6 - 53.2	38	34
DOC		mg/L	13.5 - 27.4	23.1	10.5 - 27	19.4	16.6 - 32.4	24.85	12.6 - 24.7	18.75	13.5 - 23.9	17.9	19.55
Cl.diss	600	mg/L	0.1 - 2.5	1.5	0.1 - 15.9	0.85	0.1 - 9.2	1.35	0.3 - 2	1.3	0.2 - 2.9	1.6	1.3
Cr.tot	8.9*	µg/L	0.07 - 3.76	0.115	0.04 - 2.6	0.105	0.09 - 1.24	0.17	0.05 - 0.56	0.09	0.05 - 1.79	0.11	0.125
Co.tot	110	µg/L	0.15 - 3.49	0.2745	0.093 - 2.39	0.1555	0.127 - 1.28	0.2895	0.057 - 0.978	0.159	0.06 - 2.39	0.182	0.216
Cu.tot	5.46 – 30.3*	µg/L	0.36 - 5.3	0.93	0.55 - 5.51	0.86	0.54 - 3.02	0.745	0.46 - 1.35	0.8	0.44 - 4.12	0.82	0.82
Hardness		mg/L	36.8 - 142	83.3	61.2 - 301	133.5	63.6 - 214	117	76.1 - 161	118	66 - 182	127	116
Fe.tot	1000	µg/L	**264 - 7310**	752.5	**163 - 5660**	735	**609 - 2650**	**1465**	**243 - 2310**	312	**250 - 5360**	429	593
Pb.tot	22.9 - 332*	µg/L	0.022 - 4.33	0.078	0.015 - 3.25	0.0725	0.092 - 1.57	0.2105	0.04 - 0.732	0.107	0.034 - 2.59	0.101	0.1055
Li.tot			3.2 - 10.7	6.48	2.1 - 12.1	4.995	3.56 - 9.69	5.575	4.24 - 7.67	5.77	3.4 - 8.46	6.05	5.705
Mg.diss.ext			2.2 - 9.32	5.5	3.3 - 18.4	7.75	3.8 - 13.9	7.7	4.89 - 10.3	7.94	4.13 - 12	8.07	7.17
Mn.tot	945 – 3857*	µg/L	16.4 - 372	29.85	18.1 - 193	40.35	40 - 189	85.8	12.8 - 266	49.2	9.49 - 439	60.8	49.5
Mo.tot	2000	µg/L	0.04 - 0.271	0.0915	0.243 - 2.04	0.473	0.191 - 0.721	0.379	0.256 - 0.836	0.503	0.244 - 0.981	0.488	0.488
NO_3	32.8	mg/L	< 0.002 - 0.195	0.00415	< 0.002 - 0.197	NC	< 0.002 - 0.281	NC	< 0.002 - 0.459	0.0033	< 0.002 - 0.355	0.0055	0.00335
NO_2	0.06 - 0.6**	mg/L	< 0.002 - 0.02	NC	< 0.005 - 0.0079	NC	< 0.005 - 0.015	NC	< 0.002 - 0.0072	NC	< 0.002 - 0.022	NC	70% < DL
pH	6.5 - 9.0	pH units	7.33 - 8.21	7.89	7.67 - 8.39	8.095	7.47 - 8.17	7.92	7.52 - 8.22	7.95	7.75 - 8.19	7.97	7.95

APPENDIX TABLE A5. *Con't.*

			FORTUNE N=12		EMILE N=12		SAHDOANAH N=12		PETITOT D/S TSEA N=13		PETITOT AT HIGHWAY 77 N=15		PETITOT RIVER BASIN
VARIABLE	GUIDELINE	UNITS	RANGE	MEDIAN	RANGE	MEDIAN	RANGE	MEDIAN	RANGE	MEDIAN	RANGE	MEDIAN	MEDIAN
P.tot	framework‡	µg/L	8.8 - 21.2	17.5	9.5 - 72.6	10.9	21.3 - 126	21.6	8.1 - 14.6	18.2	7.7 - 17.9	13.6	17.6
K.diss.ext			0.163 - 1.4	0.625	0.3 - 2.2	1.15	0.4 - 2	0.961	0.334 - 3.33	0.84	0.28 - 1.66	0.963	0.899
TDS	500†	mg/L	64 - 250	138	ND	NC	ND	NC	124 - 222	173	106 - 260	181	170
TSS			<1 - 328	2.5	3 – 157	3.6	<2 - 110	16	1.6 - 134	3.9	<1 - 81.5	6.1	4.8
Rb.tot			0.486 - 7.35	1.0145	0.592 - 4.9	1.085	0.53 - 2.78	0.9145	0.614 - 3.78	0.808	0.553 - 4.46	0.934	0.926
Na.diss.ext	200†		1.22 - 15.1	4.62	1.1 - 27.6	3	1.7 - 20.9	4	2.6 - 6.66	4.33	2 - 8.64	4.39	4.33
Se.tot	2	µg/L	0.04 - 0.3	0.07	< 0.01 - 0.23	0.14	0.08 - 0.19	0.12	<0.01 - 0.22	0.07	< 0.01 - 0.2	0.1	0.1
Sp.cond			79.2 - 333	179	121 - 644	241	125 - 479	229	170 - 331	242	141 - 378	255	224
Sr.tot	10,700§		40.6 - 144	88.6	40.1 - 217	84.75	44 - 156	78.15	56.1 - 110	77.4	47 - 127	87.4	79.25
SO_4	218 - 429*	mg/L	5.34 - 63.4	21.55	8.86 - 67	26.6	14.8 - 69.1	36.5	16.7 - 47.3	28	14.4 - 44.4	29.3	28.25
U.tot			0.0406 - 0.407	0.106	0.199 - 2.09	0.483	0.175 - 0.763	0.355	0.185 - 0.451	0.312	0.212 - 0.702	0.41	0.3495
V.tot			0.118 - 6.24	0.2705	0.161 - 4.69	0.2555	0.274 - 2.34	0.5475	0.162 - 1.32	0.327	0.136 - 3.51	0.39	0.35
Zn.tot	33 – 191*	µg/L	0.8 - 25.7	1.25	0.2 - 26	0.75	0.9 - 12.2	1.7	0.5 - 6.1	0.8	0.5 - 17.2	0.8	1.15

* based on Hardness
** based on Cl concentration < 2 mg/L
*** Environmental Quality Guidelines for Alberta Surface Waters
† Health Canada Drinking Water Guideline
‡ Canadian Water Quality Guidelines for the Protection of Aquatic Life
§ Proposed chronic effects benchmark (McPherson et al. 2014)
ND: no data
NC: not calculated
DL: detection limit

APPENDIX TABLE A6. *Results of the Kruskal Wallis and pairwise Wilcoxon tests for between-site differences. Kruskal-Wallis test results are indicated below variable names. Significant values are highlighted. Water chemistry at Fortune Creek appears to differ consistently from the other sites.*

VARIABLE		FORTUNE	EMILE	SAHDOANAH	PETITOT.TSEA
Alk.tot	Emile Creek	0.029			
0.019	Sahdoanah River	0.29	0.29		
	Petitot River downstream of Tsea River	0.029	0.60	0.46	
	Petitot River at Highway 77	0.029	0.63	0.44	0.61
As.tot	Emile Creek	0.11			
0.029	Sahdoanah River	0.061	0.70		
	Petitot River downstream of Tsea River	0.064	0.89	0.47	
	Petitot River at Highway 77	0.064	0.77	0.47	0.77
Ba.tot	Emile Creek	0.0014			
0.00017	Sahdoanah River	0.0031	0.17		
	Petitot River downstream of Tsea River	0.0021	0.17	0.89	
	Petitot River at Highway 77	0.0005	0.44	0.17	0.31
Ca.diss.ext	Emile Creek	0.027			
0.02	Sahdoanah River	0.064	0.59		
	Petitot River downstream of Tsea River	0.027	0.59	0.81	
	Petitot River at Highway 77	0.027	0.77	0.61	0.79
Cd.tot	Emile Creek	0.094			
0.0064	Sahdoanah River	0.030	0.65		
	Petitot River downstream of Tsea River	0.66	0.030	0.030	
	Petitot River at Highway 77	0.21	0.40	0.21	0.12
DIC	Emile Creek	0.061			
0.021	Sahdoanah River	0.31	0.39		
	Petitot River downstream of Tsea River	0.061	0.77	0.39	
	Petitot River at Highway 77	0.031	0.96	0.37	0.53
DOC	Emile Creek	0.20			
0.0021	Sahdoanah River	0.14	0.06		
	Petitot River downstream of Tsea River	0.062	0.55	0.015	
	Petitot River at Highway 77	0.062	0.30	0.012	0.84
Fe.tot	Emile Creek	0.79			
0.0056	Sahdoanah River	0.040	0.20		
	Petitot River downstream of Tsea River	0.20	0.20	0.0014	
	Petitot River at Highway 77	0.79	0.87	0.031	0.22
Hardness	Emile Creek	0.033			
0.013	Sahdoanah River	0.056	0.79		
	Petitot River downstream of Tsea River	0.023	0.79	0.81	
	Petitot River at Highway 77	0.023	0.79	0.79	0.79

APPENDIX TABLE A6. *Con't.*

VARIABLE		FORTUNE	EMILE	SAHDOANAH	PETITOT.TSEA
Mg.diss.ext	Emile Creek	0.031			
0.008	Sahdoanah River	0.031	1.0		
	Petitot River downstream of Tsea River	0.008	1.0	0.99	
	Petitot River at Highway 77	0.008	1.0	1.0	1.0
Mn.tot	Emile Creek	0.58			
0.043	Sahdoanah River	0.027	0.10		
	Petitot River downstream of Tsea River	0.58	0.82	0.15	
	Petitot River at Highway 77	0.55	0.82	0.20	0.82
Mo.tot	Emile Creek	7.4E-06			
7.40E-06	Sahdoanah River	4.9E-06	0.73		
	Petitot River downstream of Tsea River	3.8E-06	1.0	0.30	
	Petitot River at Highway 77	2.3E-06	1.0	0.46	1.0
pH	Emile Creek	0.083			
0.042	Sahdoanah River	0.36	0.20		
	Petitot River downstream of Tsea River	0.22	0.22	0.75	
	Petitot River at Highway 77	0.20	0.22	0.75	0.75
Sp.cond	Emile Creek	0.069			
0.024	Sahdoanah River	0.069	0.89		
	Petitot River downstream of Tsea River	0.033	0.97	0.77	
	Petitot River at Highway 77	0.033	1.0	0.77	0.77
U.tot	Emile Creek	0.0001			
1.40E-05	Sahdoanah River	0.0002	0.43		
	Petitot River downstream of Tsea River	0.0002	0.14	0.20	
	Petitot River at Highway 77	5.2E-05	0.52	0.45	0.040
Zn.tot	Emile Creek	0.22			
0.04	Sahdoanah River	0.47	0.16		
	Petitot River downstream of Tsea River	0.16	1.0	0.14	
	Petitot River at Highway 77	0.20	0.64	0.16	0.64

APPENDIX TABLE A7. *Results of the Kruskal Wallis and pairwise Wilcoxon tests between seasons. Kruskal-Wallis test results are indicated below variable names. Significant values are highlighted. All measured water chemistry variables showed significant seasonality with the exception of dissolved organic carbon (DOC) and uranium (U). Note that the consistent differences in water chemistry in spring are likely the effect of freshet.*

VARIABLE		SPRING	SUMMER	FALL
Al.tot	summer	1.2E-09		
3.4E-09	fall	5.8E-07	0.18	
	winter	1.7E-08	0.0096	0.26
Alk.tot	summer	7.9E-07		
8.2E-09	fall	0.0044	0.18	
	winter	3.5E-08	0.0033	0.0044
As.tot	summer	0.0013		
3.5E-08	fall	0.00016	0.0015	
	winter	2.0E-05	0.00079	0.38
B.tot	summer	1.3E-05		
3.4E-07	fall	0.43	0.19	
	winter	1.3E-05	0.0093	0.0093
Ba.tot	summer	0.72		
0.0064	fall	0.14	0.14	
	winter	0.14	0.021	0.0033
Be.tot	summer	6.1E-07		
9.6E-10	fall	6.8E-05	0.0083	
	winter	9.9E-06	0.0020	0.15
Ca.diss.ext	summer	3.8E-06		
8.6E-08	fall	0.0086	0.23	
	winter	4.1E-07	0.011	0.011
Cd.tot	summer	3.1E-06		
4.6E-09	fall	5.8E-05	0.010	
	winter	1.1E-05	0.0092	0.74
Cl.diss	summer	0.018		
0.0001	fall	0.11	0.89	
	winter	0.00035	0.0080	0.018
Co.tot	summer	2.2E-07		
2.4E-10	fall	5.8E-05	0.013	
	winter	7.1E-06	0.00044	0.077
Cr.tot	summer	5.7E-07		
6.0E-09	fall	7.1E-05	0.26	
	winter	8.4E-06	0.027	0.26
Cu.tot	summer	2.5E-06		
3.2E-09	fall	0.00012	0.00023	
	winter	5.1E-05	0.12	0.010
DIC	summer	8.1E-06		
3.8E-08	fall	0.0087	0.22	
	winter	3.5E-08	0.0029	0.0029
Fe.tot	summer	1.6E-06		
1.4E-07	fall	6.1E-06	0.88	
	winter	7.9E-05	0.12	0.12
Hardness	summer	1.3E-05		
1.4E-07	fall	0.012	0.30	
	winter	1.5E-05	0.012	0.012
K.diss.ext	summer	4.8E-05		
3.6E-07	fall	0.00045	0.53	
	winter	0.014	0.0011	0.0018

VARIABLE		SPRING	SUMMER	FALL
Li.tot	summer	0.00030		
9.4E-07	fall	0.011	0.83	
	winter	6.6E-07	0.0039	0.011
Mg.diss.ext	summer	2.6E-05		
3.1E-07	fall	0.0060	0.53	
	winter	1.0E-06	0.0060	0.030
Mn.tot	summer	0.029		
2.2E-05	fall	0.0048	0.057	
	winter	0.00015	0.0048	0.39
Mo.tot	summer	0.032		
0.011	fall	0.85	0.22	
	winter	0.011	0.85	0.22
Na.diss.ext	summer	7.1E-06		
9.3E-09	fall	0.0012	0.60	
	winter	7.1E-06	0.0012	0.0013
NO_2	summer	0.00017		
0.0003	fall	0.21	0.22	
	winter	0.69	0.0089	0.33
NO_3	summer	0.0090		
1.6E-07	fall	0.21	0.14	
	winter	0.00010	5.04E-06	0.00021
Pb.tot	summer	2.2E-07		
2.8E-09	fall	5.8E-05	0.33	
	winter	7.1E-06	0.025	0.13
pH	summer	1.6E-06		
9.8E-08	fall	0.0035	0.097	
	winter	1.2E-05	0.22	0.32
Rb.tot	summer	5.8E-07		
4.8E-10	fall	4.3E-05	0.00015	
	winter	8.0E-06	0.65	8.04E-06
SO_4	summer	0.049		
0.0008	fall	0.049	0.40	
	winter	0.0029	0.019	0.16
Sp.cond	summer	2.3E-05		
1.2E-07	fall	0.0044	0.52	
	winter	4.1E-07	0.0029	0.0082
Sr.tot	summer	1.5E-06		
3.7E-09	fall	0.00028	0.21	
	winter	7.1E-06	0.0026	0.0026
TSS	summer	7.6E-07		
8.1E-09	fall	1.9E-06	0.40	
	winter	2.4E-05	0.0043	0.069
V.tot	summer	8.8E-07		
2.5E-10	fall	5.8E-05	0.0031	
	winter	7.1E-06	0.00015	0.39
Zn.tot	summer	2.1E-07		
8.1E-09	fall	5.7E-05	0.90	
	winter	7.0E-06	0.30	0.30

APPENDIX TABLE A8. *Continuous water temperature data from May 2013 to July 2015 at each site was compared with the British Columbia guideline for the protection of aquatic life (19°C, unknown fish distributions) and aggregated by month. Shown are the number of days in each month where water temperature exceeded the guideline (19°C) and the percentage of days that exceeded based on the available data. July had the most days exceeding the guideline at all sites.*

	FORTUNE			EMILE			SAHDOANAH			PETITOT DS TSEA			PETITOT AT HIGHWAY 77		
	% COMPLETE	N > 19°C	% DAYS EXCEEDING	% COMPLETE	N >19°C	% DAYS EXCEEDING	% COMPLETE	N > 19°C	% DAYS EXCEEDING	% COMPLETE	N > 19°C	% DAYS EXCEEDING	% COMPLETE	N > 19°C	% DAYS EXCEEDING
Jan	50.0	0	0	100.0	0	0	100.0	0	0	79.0	0	0	79.0	0	0
Feb	50.0	0	0	100.0	0	0	100.0	0	0	50.0	0	0	50.0	0	0
Mar	50.0	0	0	100.0	0	0	100.0	0	0	50.0	0	0	50.0	0	0
Apr	50.0	0	0	100.0	0	0	100.0	0	0	50.0	0	0	50.0	0	0
May	61.3	4	7	66.7	7	11	90.3	0	0	33.3	7	23	55.9	7	13
Jun	66.7	14	23	66.7	25	42	100.0	17	19	33.3	21	70	66.7	36	60
Jul	**68.8**	**39**	**59**	**65.6**	**54**	**86**	**79.6**	**34**	**45**	**35.5**	**31**	**89**	**46.2**	**40**	**91**
Aug	100.0	17	27	100.0	37	60	100.0	23	37	82.3	35	67	82.3	28	54
Sep	100.0	0	0	100.0	0	0	100.0	0	0	100.0	0	0	100.0	0	0
Oct	100.0	0	0	100.0	0	0	100.0	0	0	100.0	0	0	100.0	0	0
Nov	100.0	0	0	100.0	0	0	100.0	0	0	100.0	0	0	100.0	0	0
Dec	93.5	0	0	100.0	0	0	100.0	0	0	100.0	0	0	100.0	0	0

Minimum daily temperatures were calculated using the raw continuous data collected at 30 minute intervals.
The percentage of days that exceeded in the month was calculated by dividing the total number of days that exceeded 19 C by the total number of days in the month where there was data.

APPENDIX B

APPENDIX TABLE B1. *Suite of variables for the base synoptic program with detection limits, method and analytical labs. PYLET = Pacific and Yukon Laboratory for Environmental Testing, North Vancouver, BC; NLET = National Laboratory for Environmental Testing, Burlington, ON.*

VARIABLE	DL	UNITS	METHOD	LAB
GENERAL VARIABLES				
Alkalinity pH 4.5	0.5	mg $CaCO_3$/L	titration	PYLET
Chloride (Cl)	0.1	mg/L	ICA	PYLET
Fluoride (F)	0.01	mg/L	ICA	PYLET
Sulphate (SO_4)	3	mg/L	ICA	PYLET
Bromide (Br)	0.02	mg/L	ICA	PYLET
Nitrogen, Nitrate as N	0.005	mg/L	ICA	PYLET
Nitrogen, Nitrite as N	0.005	mg/L	ICA	PYLET
pH	0.01	pH Units	probe	PYLET
Solids, Total Suspended (NFR)	2	mg/L	gravimetric	PYLET
Specific Conductance (25°C)	2	µS/cm	meter	PYLET
NON-HALOGENATED ORGANICS				
Dissolved Inorganic Carbon	0.5	mg/L		PYLET
Dissolved Organic Carbon	0.5	mg/L		PYLET
NUTRIENTS				
Ammonia Nitrogen (mg N)	0.002	mg/L	FIA	PYLET
Nitrite Nitrogen (mg N)	0.002	mg/L	FIA	PYLET
Nitrate + Nitrite Nitrogen (mg N)	0.002	mg/L	FIA	PYLET
Total Nitrogen (as N)	0.02	mg/L	FIA	PYLET
Total Dissolved Phosphorus (as P)	0.0005	mg/L	FIA	PYLET
Phosphate, Total FIA	0.0005	mg/L	FIA	NLET
METALS				
Total Calcium	0.1	mg/L	ICP	PYLET
Total Magnesium	0.1	mg/L	ICP	PYLET
Total Potassium	0.1	mg/L	ICP	PYLET
Total Silicon	0.05	mg/L	ICP	PYLET
Total Sodium	0.1	mg/L	ICP	PYLET
Total Ca+Mg Hardness.	0.4	mg $CaCO_3$/L	Calc.	PYLET
Total Aluminum	0.5	µg/L	ICP-MS	NLET
Total Antimony	0.001	µg/L	ICP-MS	NLET
Total Arsenic	0.01	µg/L	ICP-MS	NLET
Total Barium	0.05	µg/L	ICP-MS	NLET

VARIABLE	DL	UNITS	METHOD	LAB
METALS (CONT.)				
Total Beryllium	0.001	µg/L	ICP-MS	NLET
Total Bismuth	0.001	µg/L	ICP-MS	NLET
Total Boron	0.5	µg/L	ICP-MS	NLET
Total Cadmium	0.001	µg/L	ICP-MS	NLET
Total Cerium	0.001	µg/L	ICP-MS	NLET
Total Cesium	0.001	µg/L	ICP-MS	NLET
Total Chromium	0.01	µg/L	ICP-MS	NLET
Total Cobalt	0.002	µg/L	ICP-MS	NLET
Total Copper	0.02	µg/L	ICP-MS	NLET
Total Gallium	0.001	µg/L	ICP-MS	NLET
Total Iron	0.5	µg/L	ICP-MS	NLET
Total Lanthanum	0.001	µg/L	ICP-MS	NLET
Total Lead	0.005	µg/L	ICP-MS	NLET
Total Lithium	0.01	µg/L	ICP-MS	NLET
Total Manganese	0.05	µg/L	ICP-MS	NLET
Total Molybdenum	0.005	µg/L	ICP-MS	NLET
Total Nickel	0.02	µg/L	ICP-MS	NLET
Total Niobium	0.001	µg/L	ICP-MS	NLET
Total Platinum	0.001	µg/L	ICP-MS	NLET
Total Rubidium	0.001	µg/L	ICP-MS	NLET
Total Selenium	0.01	µg/L	ICP-MS	NLET
Total Silver	0.001	µg/L	ICP-MS	NLET
Total Strontium	0.05	µg/L	ICP-MS	NLET
Total Thallium	0.001	µg/L	ICP-MS	NLET
Total Tin	0.005	µg/L	ICP-MS	NLET
Total Tungsten	0.001	µg/L	ICP-MS	NLET
Total Uranium	0.0005	µg/L	ICP-MS	NLET
Total Vanadium	0.005	µg/L	ICP-MS	NLET
Total Yttrium	0.001	µg/L	ICP-MS	NLET
Total Zinc	0.2	µg/L	ICP-MS	NLET

Abbreviations: ICA = ion chromatography anions; FIA = flow-injection analysis; ICP = Inductively-coupled plasma; ICP-MS = ICP-Mass spectrometry.

APPENDIX TABLE B2. *Organic variables measured by Columbia Labs, Kelso, Washington, May 2012.*

VARIABLE	ANALYTICAL METHOD
Diesel range organics	LC EPA Method 8015C
Residual range organics	LC EPA Method 8015C
Ethylene glycol	LC EPA Method 8015C
Isopropanol	LC EPA Method 8015C
2-butoxyethanol	LC EPA Method 8015C
Methanol	LC EPA Method 8015C
Ethanol	LC EPA Method 8015C
D-mannose	
D-galactose	
Glutaraldehyde	EPA Method 8315A
Citric Acid	HPLC-AO
Acetic Acid	HPLC-AO
Formic acid	HPLC-AO

APPENDIX TABLE B3. *Organic chemical variables measured by Axys Analytical Services, Sidney BC. Detection limits for PAH congeners were sample-specific but generally approximately 2 ng/L. Detection limits for Naphthenic Acid compounds were also sample specific, but generally 4-5 ng/L.*

VARIABLE	VARIABLE
Naphthenic Acids (C12 - C21)	2-Methylnaphthalene
PAHs (parent+alkylated)	1-Methylnaphthalene
Naphthalene	1,2-Dimethylnaphthalene
Acenaphthylene	2,6-Dimethylnaphthalene
Acenaphthene	2,3,6-Trimethylnaphthalene
Fluorene	2,3,5-Trimethylnaphthalene
Phenanthrene	1,4,6,7-Tetramethylnaphthalene
Anthracene	Biphenyl
Fluoranthene	Dibenzothiophene
Pyrene	3-Methylphenanthrene
Benz[a]anthracene	2-Methylphenanthrene
Chrysene	2-Methylanthracene
Benzo[b/j/k]fluoranthene	9/4-Methylphenanthrene
Benzo[b]fluoranthene	1-Methylphenanthrene
Benzo[a]pyrene	3,6-Dimethylphenanthrene
Dibenz[a,h]anthracene	2,6-Dimethylphenanthrene
Indeno[1,2,3-cd]pyrene	1,7-Dimethylphenanthrene
Benzo[ghi]perylene	1,8-Dimethylphenanthrene
Benzo[j,k]fluoranthenes	1,2,6-Trimethylphenanthrene
Benzo[e]pyrene	Retene
Perylene	

APPENDIX TABLE B4. *Volatile organic compounds with associated detection limits measured at the Pacific Environmental Science Centre, May 2012. Benzene and toluene (in **bold**) were detected at all sites near the detection limit.*

VARIABLE	DETECTION LIMIT (µG/L)
1,1-Dichloroethene	0.1
Methylene chloride	0.3
trans-1,2-Dichloroethene	0.1
1,1-Dichloroethane	0.1
cis-1,2-Dichloroethene	0.1
2,2-Dichloropropane	0.1
Bromochloromethane	0.2
Chloroform	0.2
1,1,1-Trichloroethane	0.2
1,1-Dichloropropene	0.2
Carbon tetrachloride	0.2
1,2-Dichloroethane	0.4
Benzene	**0.1**
Trichloroethene	0.05
1,2-Dichloropropane	0.2
Dibromomethane	0.2
Bromodichloromethane	0.2
Toluene	**0.05**
1,1,2-Trichloroethane	0.2
1,3-Dichloropropane	0.5
Tetrachloroethylene	0.1
Dibromochloromethane	0.1
1,2-Dibromoethane	0.1
Chlorobenzene	0.05

VARIABLE	DETECTION LIMIT (µG/L)
1,1,1,2-Tetrachloroethane	0.1
Ethylbenzene	0.1
m,p-Xylene	0.1
o-Xylene	0.05
Styrene	0.1
Bromoform	0.2
Isopropylbenzene	0.05
1,1,2,2-Tetrachloroethane	0.2
Bromobenzene	0.1
1,2,3-Trichloropropane	0.5
n-Propylbenzene	0.2
2-Chlorotoluene	0.2
1,3,5-Trimethylbenzene	0.2
4-Chlorotoluene	0.1
tert-Butylbenzene	0.05
1,2,4-Trimethylbenzene	0.1
sec-Butylbenzene	0.1
1,3-Dichlorobenzene	0.05
p-Isopropyltoluene	0.1
1,4-Dichlorobenzene	0.05
n-Butylbenzene	0.1
1,2-Dichlorobenzene	0.05
1,2-Dibromo-3-chloropropane	0.4
1,2,4-Trichlorobenzene	0.1

APPENDIX TABLE B5. *Summary statistics of water chemistry data for samples collected in 2013/2014, comparing high- and low-water periods. N is number of samples with concentrations > detection limit. Total samples for highwater period = 47; total samples for low-water period = 46.*

		HIGH WATER						LOW WATER					
VARIABLE	UNITS	N	MIN	MAX	MEAN	MEDIAN	SE	N	MIN	MAX	MEAN	MEDIAN	SE
Tot Alkalinity	mgCaCO$_3$/L	47	12.3	75.4	41.5	43.00	0.29	46	35.9	181	109.8	106.0	0.628
pH	-	47	6.95	7.96	7.69	7.77	0.00	46	7.47	8.41	8.14	8.21	0.004
Diss Inorg Carbon	mg/L	47	2.6	16.6	9.1	9.50	0.07	46	6.4	42	25.9	24.8	0.157
Diss Org Carbon	mg/L	47	17.5	29.4	23.1	23.10	0.05	46	15.2	47.7	29.2	28.0	0.184
Chloride	mg/L	47	0.05	0.6	0.2	0.20	0.00	46	0.05	0.9	0.4	0.3	0.005
Flouride	mg/L	46	0.02	0.08	0.05	0.05	0.00	43	<0.01	0.12	0.06	0.07	0.001
Sulphate	mg/L	47	4.5	78	26.4	24.70	0.39	46	0.6	59	25.3	24.7	0.277
Dissolved Calcium	mg/L	47	9.3	47.3	21.2	20.70	0.17	46	20	64.7	40.6	38.2	0.228
Dissolved Magnesium	mg/L	47	1.6	11.1	4.6	4.60	0.04	46	4.5	13.4	8.3	7.7	0.046
Dissolved Potassium	mg/L	47	0.7	2.2	1.2	1.30	0.01	46	0.2	0.9	0.6	0.5	0.004
Dissolved Sodium	mg/L	47	0.8	5.2	2.1	2.30	0.02	46	1.4	11.5	4.2	4.1	0.044
Tot Susp Solids	mg/L	47	5	283	53.5	32.00	1.17	46	1	95	8.9	5.0	0.341
Total Nitrogen	mg/L	47	0.45	0.89	0.64	0.64	0.00	46	0.48	1.14	0.77	0.71	0.003
Spec Cond	µS/cm	47	60	327	150	151.00	1.29	46	112	389	251	238	1.317
Hardness	mgCaCO$_3$/L	47	30	164	72	70.40	0.59	46	68	214	136	128	0.749
Total Silver	µg/L	47	0.003	0.086	0.017	0.01	0.00	46	0.001	0.023	0.004	0.003	0.000
Total Aluminum	µg/L	47	62.4	2260	509.6	342.00	9.69	46	13.1	567	71.0	40.7	2.319
Total Tin	µg/L	47	0.02	0.257	0.055	0.05	0.00	46	0.027	0.091	0.050	0.048	0.000
Total Arsenic	µg/L	47	0.25	2.66	0.87	0.70	0.01	46	0.39	1.51	0.77	0.71	0.005
Total Barium	µg/L	47	15.8	115	39.2	33.80	0.42	46	21.7	55.7	38.7	38.3	0.147
Total Beryllium	µg/L	47	0.007	0.194	0.048	0.03	0.00	46	0.008	0.064	0.016	0.012	0.000
Total Boron	µg/L	47	4.4	16.8	9.3	9.30	0.05	46	5.8	29.8	14.0	13.5	0.104
Total Cadmium	µg/L	47	0.01	0.282	0.060	0.04	0.00	46	0.004	0.076	0.019	0.015	0.000
Total Cerium	µg/L	47	0.18	11.2	2.268	1.40	0.05	46	0.074	2.34	0.326	0.209	0.009
Total Cesium	µg/L	47	0.009	0.523	0.130	0.10	0.00	46	0.001	0.215	0.022	0.014	0.001
Total Chromium	µg/L	47	0.12	3.47	0.82	0.57	0.01	46	0.06	0.93	0.17	0.12	0.004
Total Cobalt	µg/L	47	0.092	2.95	0.774	0.55	0.01	46	0.112	0.877	0.248	0.177	0.004
Total Copper	µg/L	47	0.32	6.99	1.88	1.35	0.03	46	0.24	2.63	0.79	0.73	0.009
Total Gallium	µg/L	47	0.02	0.881	0.193	0.12	0.00	46	0.005	0.22	0.027	0.017	0.001
Total Iron	µg/L	47	247	6240	1773	1240.00	28.46	46	232	5860	946	676	21.181
Total Lathanium	µg/L	47	0.08	4.75	0.957	0.60	0.02	46	0.039	0.965	0.147	0.096	0.004
Total Lead	µg/L	47	0.102	4.25	0.971	0.66	0.02	46	0.031	1.04	0.150	0.095	0.004
Total Lithium	µg/L	47	1.64	8.02	4.03	4.04	0.03	46	2.32	14.1	6.01	5.42	0.049
Total Manganese	µg/L	47	17.2	153	58.9	51.60	0.60	46	19.5	288	63.5	55.4	0.945
Total Molybdenum	µg/L	47	0.092	0.437	0.268	0.29	0.00	46	0.157	0.694	0.426	0.427	0.003
Total Nickel	µg/L	47	0.38	7.86	2.22	1.66	0.03	46	0.69	5.23	1.41	1.13	0.019
Total Niobium	µg/L	47	0.002	0.116	0.023	0.02	0.00	27	<0.001	0.035	0.006	0.004	0.000
Total Platinum	µg/L	10	0.001	0.001	0.001	0.00	0.00	12	<0.001	0.001	0.001	0.001	0.000
Total Rubidium	µg/L	47	0.768	7.18	2.105	1.73	0.03	46	0.366	2.65	0.877	0.812	0.007
Total Selenium	µg/L	46	0.03	0.25	0.1	0.09	0.00	46	0.08	0.23	0.1	0.1	0.001
Total Strontium	µg/L	47	20.7	125	53.4	53.80	0.47	46	49.7	170	99.5	88.1	0.669
Total Thallium	µg/L	47	0.002	0.095	0.021	0.02	0.00	46	<0.001	0.031	0.006	0.004	0.000
Total Tungsten	µg/L	28	0.001	0.009	0.004	0.00	0.00	21	0.001	0.003	0.001	0.001	0.000
Total Uranium	µg/L	47	0.105	2.09	0.329	0.26	0.01	46	0.097	1.020	0.361	0.335	0.004
Total Vanadium	µg/L	47	0.24	6.74	1.610	1.15	0.03	46	0.173	1.770	0.446	0.347	0.008
Total Yttrium	µg/L	47	0.086	4.51	0.977	0.63	0.02	46	0.079	1.180	0.238	0.147	0.005
Total Zinc	µg/L	47	1.2	26.1	6.8	4.60	0.12	46	0.4	7.2	1.3	0.8	0.028

APPENDIX C

APPENDIX TABLE C1. *Geospatial data layers and sources used during initial site selection. A total of 1016 microbasins were delineated for site selection purposes. Acronyms are BC MEMRH: BC Ministry of Energy and Mines and Responsible Housing; NRC: Natural Resources Canada; BCMOE: BC Ministry of Environment; MFLNRO: BC Ministry of Forests, Lands and Natural Resource Operations; BCOGC: BC Oil and Gas Commission.*

REFERENCE	LAYER	DESCRIPTION	SCALE	DATE OF DATA	DATE ACCESSED	ACCESS/LINK
CLIMATE						
NRC	Climate	Historical Climate data 1971-2001 (raster dataset)	7.5 km	NA	Apr. 2013	contact: Dan McKenney - dan.mckenney@nrcanrncan.gc.ca
ELEVATION						
GeoBase - NRC	CDED	Canadian Digital Elevation Data (CDED) (raster dataset)	1:50 000 (25m)	Jun. 2007	Apr. 2013	www.geobase.ca
GEOLOGY						
BC MEMRH	NO10_geology_alb	Detailed geology in 94 region (Northeast BC)	1:250 000	2005	May 2012	
CanSIS - NRC - Agriculture and Agrifood Canada	PED_SLC_DERIVED_ V3_2_CT1 M	Drainage and geology polygons in BC	1:1 000 000	2011, updated July 2013	Apr. 2012, Apr. 2014	http://open.canada.ca/data/en/dataset
GeoGratis - NRC - Geological Survey of Canada	geo_cov	Geoscape Canada - A Map of Canada's Earth Materials - Surficial and bedrock geology	1:5 000 000	Jun. 2002	Apr. 2013	http://geogratis.gc.ca/api/en/nrcan-rncan/essst/9636bf0e-aba3-59c3-9736-1ac66bab4ac0.html?pk_campaign=recentItem
HYDROLOGY						
BC MEMRH	NO10_lake_alb	Lakes in 94 region (Northeast BC)	1:250 000	2005	May 2012	www.empr.gov.bc.ca/MINING/GEOSCIENCE/PUBLICATIONSCATALOGUE/GEOFILES/Pages/2005-10.aspx
DataBC - BCMOE	lwssbcgzl	WaterShedAtlas50K - Stream centrelines with Streamorder data	1:50 000	Jun. 2005	Apr.2007	www.env.gov.bc.ca/esd/distdata/ecosystems/bc50kwsa/shapefiles/
GeoBase - NRC	NHN_NLFLOW (multiple)	National Hydro Network, Canada network linear flow	1:50 000 or better	Feb. 2012	Apr. 2013	www.geobase.ca/
GeoBase - NRC	NHN_WATERBODY (multiple)	Waterbodies	1:50 000 or better	Feb. 2012	Apr. 2013	
DataBC - BCMOE	lwsdbcgz	WaterShedAtlas50K - Drainage areas Microbasin polygons	1:50 000	Jun. 2005	Apr.2007	www.env.gov.bc.ca/esd/distdata/ecosystems/bc50kwsa/shapefiles/
DataBC - BCMOE	lwsgbc	Catchment basins - subbasin	1:50 000	Jun. 2005	Apr.2007	www.env.gov.bc.ca/esd/distdata/ecosystems/bc50kwsa/shapefiles/
Open Data	canadfda_p	Catchment basin for Petitot and Hay (Fort Nelson is divided into smaller basins in this file)	1:1 000 000	May. 2003	Apr. 2008	
Open Data	canadnasscb_p	Catchment basin (Fort Nelson)	1:1 000 000	May. 2003	Apr. 2008	

APPENDIX TABLE C1. *Con't.*

REFERENCE	LAYER	DESCRIPTION	SCALE	DATE OF DATA	DATE ACCESSED	ACCESS/LINK
LAND COVER						
CanSIS - NRC - Agriculture and Agrifood Canada	Ecoregions	Ecoregions in BC	1:1 000 000	1996	Sept. 2009	http://sis.agr.gc.ca/cansis/nsdb/ecostrat/gis_data.html
CanSIS - NRC - Agriculture and Agrifood Canada	Ecodistricts	Ecodistricts in BC	1:1 000 000	1996	Sept. 2009	http://sis.agr.gc.ca/cansis/nsdb/ecostrat/gis_data.html
GeoBase - NRC	LCC (multiple)	Land Cover, circa 2000 Vector	1:50 000	May. 2009	Apr. 2012	www.geobase.ca
GeoGratis - NRC - Geological Survey of Canada	p_frost	Geoscape Canada - A Map of Canada's Earth Materials - perma frost coverage	1:5 000 000	Jun. 2002	Apr. 2013	http://geogratis.gc.ca/api/en/nrcan-rncan/esssst/092b663d-198b-5c8d-9665-fa3f5970a14f.html
LAND USE						
DataBC - BCMOE	BTM_PLU_V1	Land use and elevation data 1992-1997	1:250 000	2011	May 2012	https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?from=search&edit=true&showall=showall&recordSet=ISO19115&recordUID=43171
DataBC - MFLNRO	H_FIRE_PLY_polygon	Wildfires in BC	NA	Mar. 2015	Apr. 2015	
OIL AND GAS						
Data-BC BCOGC	Unconv_ply	Horn River Basin – Unconventional Plays in BC	NA	Mar. 2010	Mar. 2012	
BCOGC	AAPR_BC	Petroleum access permanent roads	NA	2011- 2015 ongoing	Feb 2012, Nov. 2014	www.bcogc.ca/publiczone/gis.aspx
BCOGC	APDR_BC	Petroleum development roads	NA	2011- 2015 ongoing	Feb 2012, Nov. 2014	www.bcogc.ca/publiczone/gis.aspx
BCOGC	SYD_ROAD	Sierra-Yoyo-Desan-Road	NA	2011- 2015 ongoing	Feb 2012, Nov. 2014	www.bcogc.ca/publiczone/gis.aspx
BCOGC	TPRD_NEBC	Petroleum development roads	NA	2011- 2015 ongoing	Feb 2012, Nov. 2014	www.bcogc.ca/publiczone/gis.aspx
BCOGC	AS8WA_BC	Short term use of water (Section 8 *Water Act*)	NA	2011- 2015 ongoing	Feb 2012, Nov. 2014	www.bcogc.ca/publiczone/gis.aspx
BCOGC	AS9WA_BC	Change in and about a stream (Section 9 *Water Act*)	NA	2011- 2015 ongoing	Feb 2012, Nov. 2014	www.bcogc.ca/publiczone/gis.aspx
BCOGC	AWCC_BC	Water Course Crossing	NA	2011- 2015 ongoing	Feb 2012, Nov. 2014	www.bcogc.ca/publiczone/gis.aspx
BCOGC	AFCLTY_BC	Facility Locations	NA	2011- 2015 ongoing	Feb 2012, Nov. 2014	www.bcogc.ca/publiczone/gis.aspx
BCOGC	AFSIT_BC	Facility Sites in BC	NA	2011- 2015 ongoing	Feb 2012, Nov. 2014	www.bcogc.ca/publiczone/gis.aspx
BCOGC	AGEO_BC	Seismic features 2006 - present	NA	2011- 2015 ongoing	Feb 2012, Nov. 2014	www.bcogc.ca/publiczone/gis.aspx
BCOGC	AGPHYS2002_2006	Seismic features 2002-2006	NA	2011- 2015 ongoing	Feb 2012, Nov. 2014	www.bcogc.ca/publiczone/gis.aspx
BCOGC	AGPHYS19962004	Seismic features 1996-2004	NA	2011- 2015 ongoing	Feb 2012, Nov. 2014	www.bcogc.ca/publiczone/gis.aspx
BCOGC	APROW_BC	Pipeline rights of way for BC	NA	2011- 2015 ongoing	Feb 2012, Nov. 2014	www.bcogc.ca/publiczone/gis.aspx

APPENDIX TABLE C1. *Con't.*

REFERENCE	LAYER	DESCRIPTION	SCALE	DATE OF DATA	DATE ACCESSED	ACCESS/LINK
OIL AND GAS CONT'D						
BCOGC	ADSIP_BC	Waste disposal sites for BC	NA	2011- 2015 ongoing	Feb 2012, Nov. 2014	www.bcogc.ca/publiczone/gis.aspx
BCOGC	ASUMP_BC	Locations of drilling waste disposal	NA	2011- 2015 ongoing	Feb 2012, Nov. 2014	www.bcogc.ca/publiczone/gis.aspx
BCOGC	AWSH_BC	Oil and gas well surface locations in BC	NA	2011- 2015 ongoing	Feb 2012, Nov. 2014	www.bcogc.ca/publiczone/gis.aspx
BCOGC	AWSIT_BC	Well sites for BC	NA	2011- 2015 ongoing	Feb 2012, Nov. 2014	www.bcogc.ca/publiczone/gis.aspx
BCOGC	Pipeline_Incide nts	Pipeline incidents	NA	Dec. 2014	Mar. 2015	www.bcogc.ca/publiczone/gis.aspx
BC MEMRH	NO10_communities_ 2M_alb	Communities in 94 region (Northeast BC)	1:250 000	2005	May 2012	www.empr.gov.bc.ca/MINING/GEOSCIENCE/ PUBLICATIONSCATALOGUE/GEOFILES/ Pages/2005-10.aspx
BC MEMRH	NO10_rail_alb	Railway in 94 region (Northeast BC)	1:250 000	2005	May 2012	www.empr.gov.bc.ca/MINING/GEOSCIENCE/ PUBLICATIONSCATALOGUE/GEOFILES/ Pages/2005-10.aspx
OpenData - Statistics Canada	lrnf000r_14a_e	Road Network File 2014	NA	May. 2014	Mar. 2015	

APPENDIX TABLE C2. *Descriptive metrics for the community assemblages of each reference group.*

	GROUP 1 (N=6)		GROUP 2 (N=14)		GROUP 3 (N=29)	
	MEAN ± SD	(RANGE)	MEAN ± SD	(RANGE)	MEAN ± SD	(RANGE)
COMMUNITY METRIC						
Abundance	**823.5±241.3**	**(488-1167.8)**	**421.3±172.5**	**(200-815.3)**	**2563.3±1249.4**	**(1073.3-5283.2)**
Simpson's Diversity	0.85±0.05	(0.73-0.88)	0.76±0.10	(0.45-0.88)	0.75±0.10	(0.51-0.89)
Pielou's Evenness	0.75±0.05	(0.67-0.81)	0.65±0.08	(0.45-0.76)	0.66±0.10	(0.48-0.83)
COMPOSITION METRICS (%)						
EPT*	62 ± 15%	(42-76%)	65 ± 14%	(42-86%)	63 ± 22%	(15-93%)
Ephemeroptera	9 ± 7%	(3-21%)	37 ± 21%	(9-70%)	36 ± 22%	(0-75%)
E that are Baetidae	64 ± 37%	(0-100%)	68 ± 33%	(9-100%)	57 ± 29%	(2-100%)
Plecoptera	23 ± 21%	(5-57%)	21 ± 21%	(0-66%)	18 ± 19%	(1-74%)
Trichoptera	29 ± 12%	(10-43%)	7 ± 5%	(2-20%)	10 ± 9%	(0-31%)
T that are Hydropsychidae	62 ± 23%	(23-87%)	51 ± 31%	(0-91%)	42 ± 34%	(0-100%)
Insects, non-EPT	25 ± 12%	(15-45%)	28 ± 11%	(11-48%)	32 ± 20%	(5-73%)
Non-insects	13 ± 6%	(6-22%)	8 ± 7%	(0-24%)	5 ± 8%	(0-39%)
Dipera+non-insects	35 ± 14%	(22-55%)	34 ± 14%	(14-57%)	36 ± 21%	(7-84%)
Chironomidae	11 ± 7%	(6-23%)	13 ± 8%	(3-25%)	16 ± 14%	(1-50%)
RICHNESS METRICS (NUMBER OF FAMILY LEVEL TAXA)						
Total Richness	21.8 ± 2.9	(17-25)	19.8 ± 5.5	(6-29)	17.3 ± 3.8	(10-28)
EPT richness	11.2 ± 1.7	(9-14)	11.1 ± 3	(4-16)	10.4 ± 2.2	(6-17)
Ephemeroptera taxa	2 ± 0.6	(1-3)	3.4 ± 1.3	(1-6)	3.4 ± 1.0	(1-6)
Plecoptera taxa	4 ± 0.9	(3-5)	4.1 ± 1.3	(1-5)	4.0 ± 1.3	(1-7)
Trichoptera taxa	5.2 ± 1.7	(3-7)	3.7 ± 1.7	(2-7)	3.0 ± 1.4	(0-6)
Non-insect taxa	1 ± 0.2	(0.8-1.4)	1.4 ± 0.9	(0.7-4.5)	1.5 ± 0.4	(0.6-2.7)

*EPT = Ephemeroptera (mayflies), Plecoptera (stoneflies), Trichoptera (caddisflies)

APPENDIX TABLE C3. *Select environmental characteristics for the three CABIN reference groups; predictor variables are highlighted.*

	GROUP 1 (N=6)			GROUP 2 (N=14)			GROUP 3 (N=29)		
	MEAN ± SD	MEDIAN	RANGE	MEAN ± SD	MEDIAN	RANGE	MEAN ± SD	MEDIAN	RANGE
LOCATION/MORPHOMETRY									
Latitude (dec deg)	59.245±0.747	59.634	58.282-59.857	59.011±0.570	59.054	58.034-59.970	58.794±0.464	58.803	57.948-59.683
Longitude (dec deg)	121.269±0.989	121.385	120.076-122.665	123.254±1.026	123.351	120.229-124.682	123.083±1.085	-123.295	120.056-124.521
Altitude (fasl)	1,314.8±256.9	1,318.50	1040.0-1607.0	1,322.9±375.7	1,318.00	843.0-2309.0	1,512.9±243.8	1,486.00	1036.0-2204.0
Drainage Area (km^2)	1453.0±3381.1	92.1	25.0-8354.4	789.1±2186.8	156.9	27.3-8354.4	784.2±2002.9	125.1	16.7-8354.4
Perimeter (km)	264.3±452.9	92.7	40.2-1186.0	171.1±296.2	87	39.5-1186.0	174.3±269.2	84	30.9-1186.0
Stream Density (m/km^2)	977.6±361.4	919	611.3-1594.8	1992.7±716.6	1919.3	730.8-3383.0	1960.1±829.8	1906	757.6-3665.1
CHANNEL									
Depth, avg (cm)	12.02±6.98	8.7	5.60-24.00	26.75±17.26	22.75	10.00-72.20	17.47±8.48	13.4	6.70-38.50
Depth, max (cm)	18.00±11.09	12.8	9.40-38.00	35.90±23.55	30.5	14.40-98.00	25.96±15.38	21	10.50-78.00
Channel Slope (m/m)	0.013±0.01	0.01	0.0025-0.027	0.011±0.007	0.009	0.001-0.028	0.009±0.006	0.007	0.0005-0.0230
Velocity, avg (m/s)	0.358±0.102	0.36	0.23-0.51	0.485±0.169	0.45	0.26-0.84	0.46±0.187	0.5	0.2-0.97
Velocity, max (m/s)	0.512±0.182	0.445	0.37-0.87	0.67±0.207	0.64	0.44-1.13	0.66±0.25	0.7	0.28-1.08
Width, bankfull (m)	23.6±28.5	6.75	3.1-69.0	23.4±19.1	14.25	4.3-60.0	27.0±21.8	20	5.3-98.0
Width, wetted (m)	9.9±14.9	3.9	1.6-40.0	16.5±15.9	9.1	2.5-53.0	15.4±20.6	8.8	1.9-98.0
SUBSTRATE									
Boulder %	6.3±6.7	5	0-16.0	9.9±13.2	5	0-45.0	2.6±3.5	1	0-16.0
Cobble %	36.5±28.1	45.5	0-62.0	43.9±17.2	44.5	0-64.0	40.1±21.2	39	2.0-82.0
Pebble %	32.0±21.5	26.5	7.0-59	26.6±13.0	22	10.0-60.0	45.3±16.3	48	2.-71.0
Gravel %	24.3±36.2	5	3.0-93.0	15.1±20.2	9	2.0-82.0	10.5±9.6	7	0-40.0
Silt/Clay %	0.83±1.2	0.5	0-3.0	4.4±6.1	1.5	0-18.0	1.3±2.2	1	0-10.0
Particle diameter, D50 (cm)	6.5±4.79	7	0.8-13.3	9.04±5.69	7.7	1.0-23.55	5.9±2.9	5.3	1.45-15.95
Particle diameter Dg (cm)	5.75±3.87	6.5	0.7-10.1	6.16±3.69	5.4	0.8-13.1	5.3±2.8	4.9	0.9-15.4
CLIMATE									
Precipitation, January (mm)	20.2±1.4	20.3	18.0-22.0	24.2±2.0	24.2	21.0-27.0	24.2±2.1	25	19.0-28.0
Precipitation, May (mm)	38.9±4.0	39	33.2-45.0	51.7±7.5	53.5	33.2-60.0	53.6±8.0	56	33.0-63.3
Precipitation, Annual (mm)	423.5±26.1	421.8	392.0-474.0	520.1±55.3	517.5	417.5-608.3	535.4±58.9	548.7	413.0-611.7
Temperature, May Min (°C)	1.85±0.3	2	1.1-2.0	1.44±0.5	1.45	0.3-2	1.2±0.5	1	0-2.0

APPENDIX TABLE C3. *Con't.*

	GROUP 1 (N=6)			GROUP 2 (N=14)			GROUP 3 (N=29)		
	MEAN ± SD	MEDIAN	RANGE	MEAN ± SD	MEDIAN	RANGE	MEAN ± SD	MEDIAN	RANGE
CLIMATE (CON'T)									
Temperature, Annual Max (°C)	3.7±1.3	3	2.2-6.0	4.2±0.9	4.4	2.2-5.5	4.2±0.9	4	2.2-6.0
Temperature, Annual Mean (°C)	-1.2±0.9	-1.3	-2.4 – 0	-0.5±0.7	-0.25	-2.4 – 0	-0.6±0.7	-0.3	-2.5 – 0
Temperature, Annual Min (°C)	-6.8±0.7	-7	-7.9 – -6.0	-6.2±0.6	-6	-7.9 – -5.5	-6.3±0.5	-6	-7.9 – -6.0
NATIONAL LANDCOVER (% UPSTREAM AREA)									
Broadleaf, Dense	0.35±0.36	0.24	0-0.93	1.76±3.03	0.46	0-11.4	0.7±0.9	0.17	0-3.0
Coniferous, Dense	4.20±4.69	2.96	0-9.91	5.11±5.61	2.24	0.02-13.1	4.5±5.1	1.32	0-12.5
Grassland	0.14±0.29	0	0-0.73	0.05±0.10	0	0-0.32	0.001±0.006	0	0-0.04
Herb	0.32±0.24	0.28	0-0.61	0.22±0.25	0.08	0-0.65	0.28±0.55	0.03	0-2.95
Shrub, Low	3.77±2.76	3.65	0.24-7.53	2.14±1.65	2.07	0.06-5.47	2.75±3.5	1.62	0.06-18.32
Shrub, tall	2.37±3.55	0.34	0-8.33	2.15±4.26	0.03	0-12.82	1.24±1.93	0.17	0-8.33
Water	1.19±1.53	0.48	0.01-3.84	2.50±3.54	0.85	0-9.8	2.24±2.8	0.93	0-10.42
Wetland, herb	3.27±4.31	1.51	1.03-11.99	2.38±3.89	0.81	0.23-12.44	2.71±4.25	1.45	0-21.32
Wetland, shrub	7.30±7.592	5.52	0.82-21.45	5.49±4.96	4.47	0.09-14.21	4.80±4.33	2.47	0.04-11.82
Wetland, treed	10.79±15.102	7.13	0-40.3	15.68±17.07	9.29	0-48.44	19.50±13.36	18.68	0-48.27
SURFICIAL GEOLOGY (% UPSTREAM AREA)									
Colluvial	15.28±30.26	0	0-75.64	3.83±7.35	0	0-18.90	3.05±16.14	0	0-88.44
Fine grained	0.05±0.12	0	0-0.30	0±0	0	0	5.46±18.26	0	0-78.06
Organic	15.86±24.57	0	0-48.59	14.69±28.54	4.2	0-100	4.51±9.73	0	0-46.55
Till blanket	62.05±31.14	52.4	24.4-100	60.33±35.45	72.7	0-100	73.49±35.34	86.7	0-100
Till veneer	6.76±16.55	0	0-40.5	20.45±33.7	3.1	0-100	12.12±27.5	0.1	0-100
TOPOGRAPHY (UPSTREAM AREA)									
Elevation, avg (m)	521.13±53.37	519.5	469.4-619.7	639.7±153.31	618.5	435.5-990.6	708.38±163.58	678	467.1-1238.5
%area with Slope <30%	99.67±0.48	99.95	99.04-100	91.19±9.2	93.9	69.64-100.00	88.65±14.35	93.2	35.4-100
%area with Slope 30-50%	0.27±0.38	0.05	0-0.76	6.59±7.20	5.1	0.002-24.73	7.19±7.19	4.8	0.0009-26.14
%area with Slope 50-60%	0.05±0.07	0.0003	0-0.15	1.12±1.23	0.5	0-3.98	1.8±2.77	0.7	0-12.30
%area with Slope >60%	0.016±0.02	0	0-0.06	1.1±1.005	0.7	0-2.39	2.36±5.44	0.6	0-29.3
Slope, max %	51.77±28.76	56	18.0-88.0	127.01±50.43	144.9	37.5-194.9	126.27±61.62	131	38.3-248.1