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Quesnel Lake Watershed Database Construction and Assessment

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Swan, C. August 2014 Hazeltine Creek Confluence with Quesnel Lake, post tailings dam breach.

Executive Summary

The Mount Polley Mining Corporation (MPMC) mines for copper and gold at the Mount Polley Mine near Quesnel Lake in British Columbia. On 4 August 2014 the tailings pond impoundment breached releasing tailings material into Polley Lake, Hazeltine Creek, and Quesnel Lake. Since the breach, government, corporate, and academic organizations have been collecting data to understand the effects of accidental tailings release on the aquatic systems. However, the data collected are not readily available to other organizations that could use the information to inform further monitoring, research, and remediation. The British Columbia Ministry of Environment & Climate Change Strategy (BCENV) asked organizations to contribute data surrounding Mount Polley from pre- and post-breach for a database. Pyle Consulting Inc. then complied the contributed data, created a searchable database, and analyzed the data to answer specific questions posed by the BCENV.

Several organizations (e.g., BCENV, MPMC, Azimuth, and University of Lethbridge) contributed water, sediment, and biological data to the database. The data were in various formats and states of completeness. We standardized the format (e.g., layout of data and units), filled in missing information (e.g., sample identification and details), and compiled the data before depositing them into the database. The database was constructed using MySQL and contains 21 tables, such as 'Waterbody', 'Limnology', and 'Fish'. Each datum in a table has a unique identifier that is used to link it to other tables in the database. The connections between tables allows for users to search for a specific waterbody or fish species for example and receive all data pertaining to that specific waterbody or species.

Using the database, we attempted to answer specific questions posed by the BCENV. Questions and corresponding responses are as follows:

1) "Are the concentrations of metals and phosphorus higher in Quesnel Lake and other affected waterbodies (e.g., Polley Lake and Hazeltine Creek) post-breach than pre-breach? How do the concentrations of metals and nutrients compare to the BCENV water quality guidelines (WQG) and sediment quality guidelines (SQG) for the protection of freshwater aquatic life?"

   Water copper (Cu), aluminum (Al), and arsenic (As) concentrations increased post-breach. Copper (total) concentrations were elevated post-breach in Quesnel Lake, Polley Lake, Hazeltine Creek, and Edney Creek exceeding the WQG in Quesnel Lake and Hazeltine Creek. Aluminum (dissolved) increased in both Edney Creek and Polley Lake post-breach, but only concentrations in Edney Creek exceed the WQG. Arsenic (total) increased in Polley Lake and Hazeltine Creek, but did not exceed the WQG. Phosphorus (total) increased in Quesnel Lake, Polley Lake, and Hazeltine Creek post-breach, but only remain elevated years later in Polley Lake and Hazeltine

Creek. However, these concentrations have since dropped and generally are below the WQGs. Sediment Cu and As in the West Arm of Quesnel Lake exceeded the SQG post-breach and still remain around the SQG levels. Selenium (Se) concentrations exceeded SQGs both pre- and post-breach.

Total phosphorus (P) concentrations in Quesnel Lake, Polley Lake and Hazeltine Creek increased post breach. However total P levels in Quesnel Lake appear to have returned to background levels whereas concentrations in Polley Lake and Hazeltine Creek remain elevated.

2) "Are Cu and other metals associated with the tailings that were deposited into Quesnel Lake and other waterbodies (e.g., Polley Lake and Hazeltine Creek) by the breach available to biota (i.e. fish, benthic invertebrates, plankton, and amphibians)?"

   Fish were the most sampled biota for metals. However, pre-breach data are almost nonexistent and post-breach data are minimal preventing us from comparing metal concentrations in fish pre- and post-breach. Based on high levels of metals in fish tissues, it can be ascertained that metals (Cu, Al, As, and Se) are bioavailable to fish in Quesnel Lake.

3) "What effects, if any, did the breach have on the biota (i.e. fish, benthic invertebrates, plankton, and amphibians) of Quesnel Lake and the other affected waterbodies (e.g., Polley Lake and Hazeltine Creek)?"

   Other than metal accumulation by fish, benthic invertebrate and plankton communities were the only biological effect adequately sampled for analysis. Benthic invertebrate and plankton community data are limited spatially and temporally restricting our analysis to Quesnel Lake and Polley Lake. Benthic invertebrate communities in Quesnel Lake and Polley Lake, in the areas directly impacted by the breach, were dominated by metal-pollution tolerant families post-breach. Family diversity also decreased in Quesnel Lake in the areas affected by the breach. Plankton family diversity decreased and species richness increased in Polley Lake following the breach. Pre-breach plankton data was not available for Quesnel Lake or Quesnel River thus no comparisons were made.

4) “Are there any spatial or media (i.e., water, sediment, and biota) data gaps in the database?”

   The current database is incomplete since there was partial participation by organizations. There are spatial, temporal, and media gaps that limited our ability to conduct pre- and post-breach comparisons for water, sediment, and biota. Water was heavily sampled compared to sediment and biota, however, all media require more pre- and post-breach data for complete analyses.

5) “What recommendations can be made for future action?”
   We recommend the BCENV continues to work with organizations to obtain and collect data that will fill gaps in the database. To ensure that data can be easily incorporated into the database, we recommend establishing a standard sampling scheme for water, sediment, and biota.

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1. Introduction

The largest tailings impoundment breach in Canadian history occurred on 4 August 2014 at the Mount Polley mine near Likely, BC. Approximately 25 M m^3 of tailings material was accidentally released and scoured the landscape before being deposited, along with the scoured material from the landscape, into Polley Lake, Hazeltine Creek, and Quesnel Lake (Fig. 1) [1]. Tailings material rich in metals, such as copper (Cu), can pose a risk to anadromous and resident salmonids in Quesnel Lake [1]. Despite the magnitude of this environmental disaster and the importance of Quesnel Lake to the region, little has been published on the incident and only one study has been published on the breach's effects on biota in Quesnel Lake and other smaller affected waterbodies [2]. To date, numerous governmental agencies, the Mount Polley Mining Corporation (MPMC), First Nations groups, and universities have collected water, sediment, and biological data to understand the effects of the tailings release on Quesnel Lake and the surrounding environment. However, data collected by specific organizations are not readily available to the other groups. Therefore, the British Columbia Ministry of Environment & Climate Change Strategy (BCENV) envisioned a database than contains all available pre- and post-breach data on the water, sediment, and aquatic biota of the affected region from all involved organizations. On behalf of the BCENV, we complied data contributed by various organizations, created a searchable database, and analyzed the data to answer the following questions:

1) Are the concentrations of metals and phosphorus higher in Quesnel Lake and other affected waterbodies (e.g., Polley Lake and Hazeltine Creek) post-breach than pre-breach? How do the concentrations of metals and nutrients compare to the BCENV water quality guidelines (WQG) and sediment quality guidelines (SQG) for the protection of freshwater aquatic life?
2) Are Cu and other metals associated with the tailings that were deposited into Quesnel Lake and other waterbodies (e.g., Polley Lake and Hazeltine Creek) by the breach available to biota (i.e. fish, benthic invertebrates, plankton, and amphibians)?
3) What effects, if any, did the breach have on the biota (i.e. fish, benthic invertebrates, plankton, and amphibians) of Quesnel Lake and the other affected waterbodies (e.g., Polley Lake and Hazeltine Creek)?
4) Are there any spatial or media (i.e., water, sediment, and biota) data gaps in the database?
5) What recommendations can be made for future action?

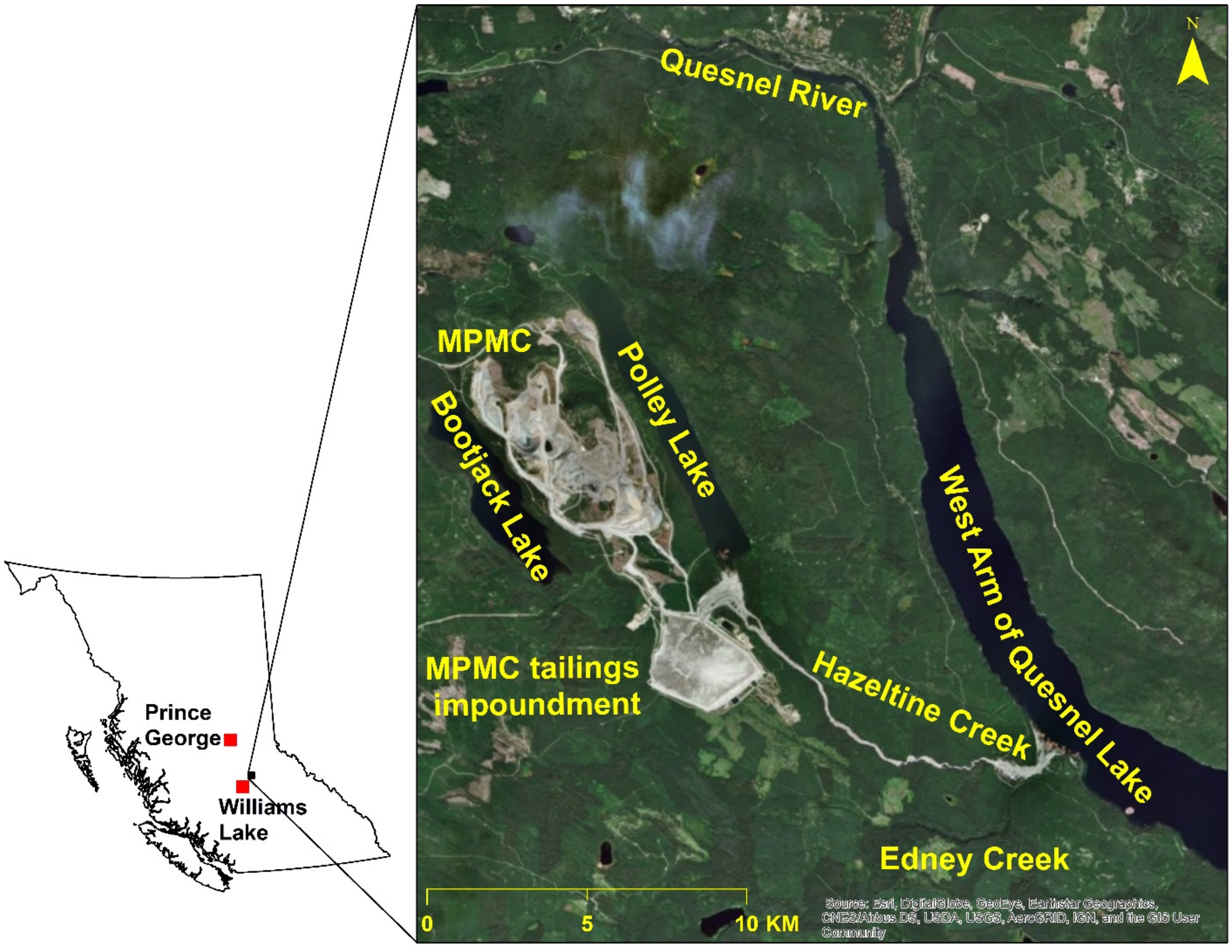

Figure 1. Map of the area impacted by the Mount Polley Mining Corporation (MPMC) tailings impoundment breach after the breach occurred.

2. Methods

2.1. Data collection and quality

BCENV requested data for the database from Fisheries and Oceans Canada (DFO), MPMC, Quesnel River Research Centre (QRRC), Azimuth, University of Lethbridge (ULeth), University of Northern British Columbia (UNBC), and First Nations Health Authority (FNHA). We received 4,946 files from the BCENV, MPMC, Azimuth, ULeth, and UNBC. Some data received from BCENV included data collected by or on behalf of other groups including DFO, MPMC, and FNHA. The files received were a mixture of reports, requisitions for analyses, analytical reports, field notes, secondary (summary) reports, maps, photos, data sheet templates, and email correspondences. All files were included in the database. However, we only used raw water, sediment, and biota (i.e., fish, benthic invertebrates, plankton, and amphibians) data from the files to answer the aforementioned questions posed by the BCENV (see section

1). Throughout this report, the word ‘file’ refers to those files containing raw data used for the analyses in this report. The quality of the files varied tremendously as they were from numerous organizations and individuals spanning decades. General issues with data collection and file quality included 1) partial participation by data holders, 2) untimely contributions by collaborators, 3) duplication of files and data, 4) inconsistent file and data format, and 5) incomplete information. We created procedures to overcome these shortcomings in order to generate the database (see subsections 2.1.1–2.1.4) and analyze the data (see section 3). Issues specific to certain database tables are discussed in subsection 2.2.3.

2.1.1. Duplication of files and data

Of the 4,946 files received, 359 files were duplicates and excluded from the database. Thus, only 4,587 files were included in the database. In addition to duplicated files, data were duplicated in the form of 1) multiple versions of analytical reports and 2) secondary (summary) reports. There were often multiple versions of the same analytical report (e.g., drafts and final). We used the final version of the analytical report when available or the most recent draft of the report. Secondary reports often repeated several years’ worth of data, which had often been manipulated for a specific purpose by the authors of the report. Therefore, we preferred to extract raw data from primary source files such as analytical reports rather than from subsequent, secondary reports. However, where possible, we extracted raw data from secondary reports to help fill data gaps. In these cases, extra care was taken to ensure no duplicated data were entered into the database. No summarized data (e.g., means) or duplicated data (e.g., field duplicates and other QA/QC data) were entered into the database with the exception of benthic invertebrate data (see subsection 2.2.3.8).

2.1.2. Inconsistent file and data format

The file format (e.g., .pdf, .xls, .csv, .docx, and .pptx) and content (e.g., metals analyzed) varied by and within file type (e.g., analytical report, secondary reports, and field notes) complicating data extraction. For example, data in .xls and .csv files were easily manipulated and extracted, while data from .pdf files needed to be entered manually or extracted using a computer script specific for each organizations’ analytical reports (e.g., Maxxam and ALS) in order to match the content and organization of content. Data were proofed by checking 10–20% of the values randomly during entry/conversion. After data were entered into respective tables, data were visually checked for consistency within columns (e.g., to detect gross mistakes in decimal place conversions or column placements), and then approximately 10% of the data were then randomly confirmed against their source files to ensure correctness.

2.1.3. Units

Units of measure varied by organization and individual researchers. We standardized the units used for each measurement type. For example, global positioning system (GPS) coordinates are reported as decimal degrees and metal concentrations are mg/kg for dry sediment and mg/L for water. The units are recorded in each table of the database so parties using the database will know the units when searching the database and entering data into the database.

2.1.4. Incomplete information

2.1.4.1. Sample identification and details

In some analytical reports, samples were identified with sample identifiers (ID) assigned by the analytical laboratory (e.g., ALS and Maxxam) but not from the contributing organization (e.g., BCENV and FNHA). Without a sample ID from the contributing organization, we were unable to determine when and where the sample was collected, and for biological samples, which species and tissues were analyzed. We left the unknown information (e.g., sample date, sample site, species, and tissue) for these samples blank in the database limiting their usefulness.

2.1.4.2. Sample site

Many sample sites have multiple names because each organization uses different names for the same geographical location. We listed all sample site names for each GPS coordinate. Some organizations add sampling details (e.g., type of biota and sample depth) to the base site name. For simplicity, we removed all sampling details in sample site names. For instance, in source file 'MPMC Hazeltine Creek and Quesnel Lake Sample Locations' (SourceFileID 86), the EMS code E306457 has seven different names associated with it—QUL-ZOO-8-0m, QUL-ZOO-8-40m, QUL-ZOO-8-80m, QUL-ZOO-8-120m, QUL-ZOO-8-160m, QUL-ZOO-8-200m, and QUL-ZOO-8-240m—describing the depth at which zooplankton were sampled. Instead, we called all sites associated with EMS code E306457 QUL-ZOO-8 and preserved depth as a variable in the table of plankton data

Spatial details for sample sites (i.e., GPS coordinates and locality description) were often missing from files. In these instances, we searched complimentary files (e.g., reports and field notes) for the missing details. When possible we estimated coordinates for sample sites in Google Maps based on site maps and locality descriptions within the complimentary files. Without GPS coordinates or enough details to estimate them, we would leave coordinates blank and assign a sample site to a specific waterbody (e.g., Quesnel Lake or Polley Lake) or waterbody region (e.g., West Arm of Quesnel Lake) if known or to the category of 'unknown' waterbody.

2.1.4.3. Sample date

Sample dates were occasionally 1) missing, 2) listed as a range of dates, or 3) listed as season (e.g., spring, summer/fall, or fall) of a specific year instead of an exact date. For missing dates, we searched complimentary files (e.g., reports and field notes) for the missing details. If no specific date could be linked to the sample in question, we left the date blank in the database. For ranges of sampling dates, we chose the earliest date or, if field notes were available, the date with the highest probability of being the sampling date was assigned. For example, if 20 fish were caught on sample date A and only five fish on sample date B, sample date for A was reported for all fish. For seasons, we assigned dates to them as follows: spring as 1 May XXXX, summer/fall as 1 July XXXX, and fall as 1 October XXXX, where XXXX represented the reported year.

2.2. Database construction and organization

2.2.1. Construction and Basic Usage

A relational database was constructed using MySQL (https://www.mysql.com), which included 21 tables of unique information (see subsection 2.2.2). The primary advantage of using a relational database over a flat spreadsheet is that unique information is stored once and only once in the database, whereas spreadsheets necessarily store vast quantities of redundant information. The database software, MySQL, is freely available at the website listed above, and usually comes pre-installed on many commercial computer distributions. The database can be accessed via a terminal, or through various front-end applications. We used Querious (https://www.araelium.com/querious) when working with the database on Mac OSX and MySQL Workbench (https://www.mysql.com/products/workbench/) when working on Windows. Several other open-source and enterprise front-end applications are available to interact with the database.

The structure of the database is such that each table containing unique information is linked to related tables via relational keys, which allows for efficient search functionality using Structured Query Language (SQL) syntax (https://dev.mysql.com/doc/refman/8.0/en/sql-syntax.html). Queries can be constructed to extract information from a single table or from multiple tables simultaneously. For example, a simple query that requests all the data stored in the WaterMetals table (containing metal concentrations in water samples collected from several sites in and around the area of interest both before and after the breach), would be:

```
SELECT * FROM WaterMetals
```

The wildcard ‘*’ refers to all columns in the table WaterMetals. The output from this query may be difficult to read because some important and necessary information is stored simply as a numeric key in WaterMetals, referring to more detailed information stored in another table. For example, one of the data columns in WaterMetals is SampleSiteID. In WaterMetals, the SampleSiteID is stored as a numeric value referring to a unique record in the Site table associated with the SiteID variable. The Site table is, in turn, related to the WaterbodyRegion table in a similar manner. The column WaterbodyRegionID in the Site table refers to a unique identifier in the WaterbodyRegion table that, in turn, refers to a specific water body, whose information is stored in the Waterbody table. This relational structure allows a user to pull information from all of these tables to generate fine-grained queries. For example, let us assume we are interested in knowing Cu, As, Al, and V concentrations in Quesnel Lake prior to the breach. We could write a query such as the following to extract exactly the information we are seeking, as follows:

```sql
SELECT SampleDate as "Date", WaterbodyName as "Water Body", WaterbodyRegionName as
    "Region", Cu, `As`, Al, V

-- Table containing the data of interest
FROM WaterMetals wm

-- Allows access to related tables
JOIN Site s ON s.SiteID = wm.SampleSiteID
JOIN WaterbodyRegion wr ON wr.WaterbodyRegionID = s.WaterbodyRegionID
JOIN Waterbody wb ON wb.WaterbodyID = wr.WaterbodyID

-- Search critera to filter the resulting dataset
WHERE WaterbodyName = 'Quesnel Lake'
AND WaterbodyRegionName = 'West arm'
AND SampleDate < "2014-08-04"
```

In this example, the SELECT statement is much more selective than the wildcard we used earlier to extract all columns of data. This time, we restrict the data in the output by explicitly specifying which specific data we require. Note the tick marks '`' around 'As' in the above query. In SQL, 'As' is a restricted key word, reserved for database functionality. It is also the abbreviation for arsenic. In order for SQL to interpret As as the symbol for arsenic and not the reserved key word, the tick marks are required, marking 'As' as a literal. The FROM statement identifies the table containing the data in which we are interested. The JOIN statements are necessary for extracting information from related tables in order to produce meaningful and human-readable output. The WHERE statement limits the query results to pre-breach (SampleDate) data from the west arm (WaterBodyRegionName) of Quesnel Lake (WaterbodyName). (Note that "--" at the beginning of a query line defines a comment, which is used only for annotation purposes and is not executed as part of the query).

Queries can be constructed as simply or as complex as the user requires. Queries can be run interactively either on the command line (in a terminal or terminal emulator) or in a front-end application, such as Querious or MySQL Workbench. Queries can be saved as text files (with an .sql extension), and sourced for convenience purposes. Storing commonly used queries as .sql files dramatically improves the efficiency of complex database searches. Any output generated by a query can be exported as a comma-separated file (or .csv format), which can easily be imported into a familiar spreadsheet program, like Microsoft Excel, Apple Numbers, or LibreOffice Calc, or even statistical programs such as SPSS, SAS, or R.

2.2.2. Schema and primary keys

We created 21 tables for the database (Fig. 2; see subsection 2.2.3). Each table has a primary key that identifies each record in a table by a unique integer. For example, a single fish is assigned a primary key such as FishID 21 in the table Fish. The primary key from one table can appear in another table as a foreign key connecting records between the two tables. For example, FishID 21 from the table Fish appears in the table FishMetals (FishMetalID 1) linking FishID 21 to the metal concentrations found in that specific fish. The links formed between tables with primary and foreign keys creates the schema, or organization, of the database (Fig. 2).

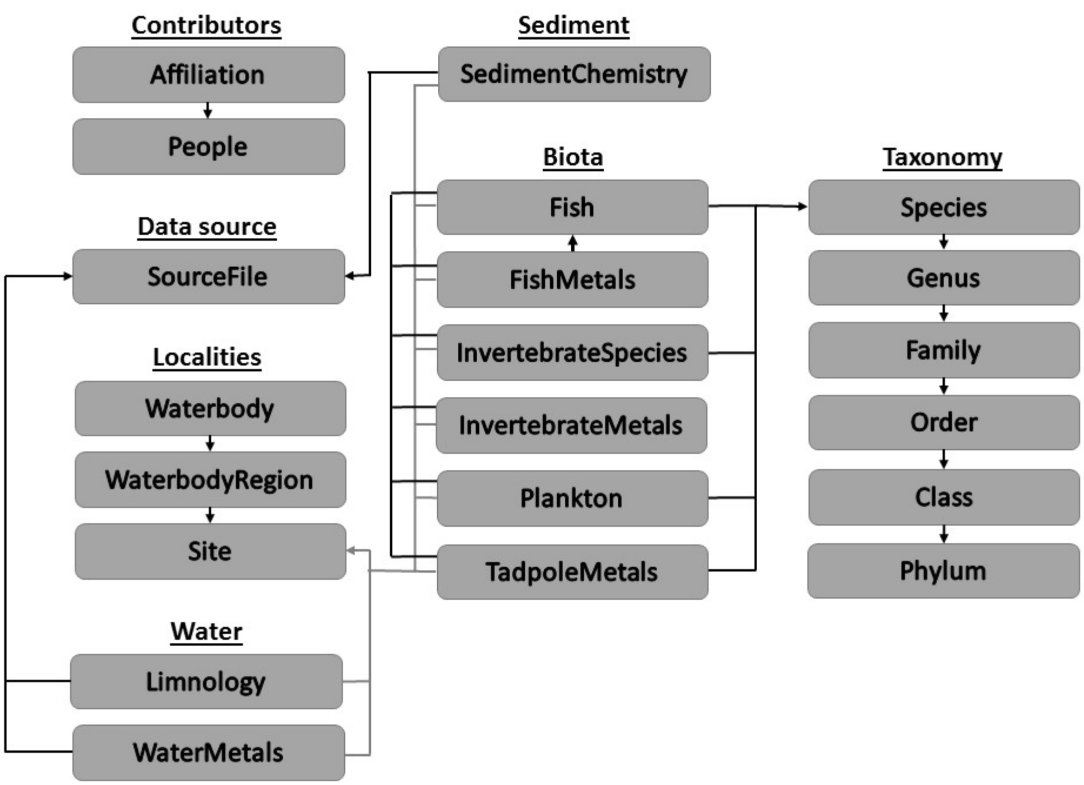

Figure 2. The schema—or organization—of the Mount Polley database. The tables in the database are represented by boxes, and the connections between those tables are represented by arrows.

2.2.3. Database tables by topic

2.2.3.1. Source files

The table SourceFile contains all files in the database. Each file has a unique ID (SourceFileID) that is used throughout the database to identify the file from which the data originated. To aid database users in searching for source files of interest, each file was given a short description that includes the content of the file (e.g., water data, photo, field notes), organization or person that created the file (e.g., MPMC, BCENV, and Swan), sample date (YYYY/MM/DD), and waterbody (not sample site; e.g., Quesnel Lake, Hazeltine Creek, and Edney Creek). There are files that appear only in SourceFiles and nowhere else in the database, because these files did not contain data required for the requested analysis.

2.2.3.2. Affiliations and people

Table 'Affiliation' includes basic information about the organizations (e.g., name, abbreviation, and address) involved with the database, while the table 'People' contains the information about people (e.g., name, affiliation, email address, and office phone numbers) from the organizations. These two tables are linked by the AffiliationID.

2.2.3.3. Locations

Tables 'Waterbody', 'WaterbodyRegion', and 'SampleSite' are nested together from broad to fine spatial scale. 'Waterbody' contains the names of all waterbodies where data were collected. 'WaterbodyRegion' lists well-known regions of specific waterbodies, such as the West Arm, East Arm, and North Arm of Quesnel Lake and the North End and South End of Polley Lake. 'SampleSite' contains the site name and GPS coordinates of sample sites within the waterbody regions and waterbodies. The primary keys from these tables are used throughout the database to identify from where data were collected and to allow users to query the database by waterbody, waterbody region, and sample site.

2.2.3.4. Water

Tables 'Limnology' and 'WaterMetals' contain water related data. 'Limnology' contains water quality variables (e.g., conductivity, alkalinity, hardness, pH, and total suspended solids), while 'WaterMetals' contains total and dissolved concentrations of metals (e.g., Al, Cu, Cd, and Se). The files containing water data were inconsistent in format and units, and missing sampling details such as depth. Therefore, we used the following procedures to standardize data compilation:

1) Lab measurements were preferred over field measurements, if both were reported;
2) Where no specific sampling depths were provided, a depth of 0 m was assumed if the source file indicated a creek or surface sample;

3) If multiple lines of data were reported in the same source file for the same sampling date, location, and depth across many time points, the first line of data that contained the most values of reported variables was entered into the database;
4) If multiple lines of data were reported in the same source file for the same sampling date, location, and depth but contained different types of variables, these lines were combined to retain available data; and
5) If water data were reported for a stream reach with no sampling coordinates, the approximate midpoint of the stream reach was estimated in Google Maps and used as the sample site coordinates in the database.

2.2.3.5. Sediment

All sediment data were compiled into table 'SedimentChemistry'. Sediment measurements, descriptions, and particle size fractions varied across files, making it impossible to compare the data. Thus, we standardized measurement units and fit particle size data to a standardized classification scheme that best described the available data (Table 1). If only general descriptions of sediment classes were reported, particle sizes of the Canadian soil classes were used to fit the data within the sediment classification scheme used in the database.

2.2.3.6. Taxonomy

The taxonomy reported for biota, especially benthic invertebrates and plankton, varied across organizations and individual taxonomists. Much of the taxonomy reported in files was outdated or tentative at more specific taxonomic levels (i.e., genus and species). Thus, we updated and standardized the taxonomy for all taxa using only the major taxonomic levels—Phylum, Class, Order, Family, Genus, and Species (Appendix 1). We updated the taxonomy to the currently accepted taxonomy using the World Register of Marine Species (WoRMS), AlgaeBase, and the Integrated Taxonomic Information System (ITIS). We removed uncertain identifications (e.g., unidentified [UID], sp., spp., and complexes) and reported taxonomy to the most specific, known taxonomic level. We created a table for each of the six taxonomic levels that are nested together based on taxonomical hierarchy (Fig. 2). In each table of biota (i.e., 'Fish', 'InvertebrateSpecies', 'Plankton', and 'TadpoleMetals'; see subsections 2.2.3.7–2.2.3.10) there is SpeciesID for each record linking it to the taxonomy tables.

Table 1. Standardized sediment classification scheme for the database. The classification scheme is based off of the soil classification schemes of the Canadian Soil Classification Working Group [3], Environment Canada [4], and United States Department of Agriculture [5]. Sediment class represents the percent of sediment that is organic particulate or the percent of mineral sediment that is finer than the particle size indicated.

Sediment class (percent of particles)	Description (percent of particles)
Organic particulate	Non-mineral fraction
Finer than bedrock/boulder	Finer than rocks of >250,000 µm
Finer than 250,000 µm	Finer than cobbles
Finer than 76,200 µm	Finer than coarse gravel
Finer than 4,750 µm	Finer than fine gravel
Finer than 2,000 µm	Finer than very coarse sand
Finer than 1,000 µm	Finer than coarse sand
Finer than 500 µm	Finer than medium sand
Finer than 250 µm	Finer than fine sand
Finer than 125 µm	Finer than very fine sand
Finer than 62 µm	Finer than very coarse silt
Finer than 31 µm	Finer than coarse silt
Finer than 16 µm	Finer than medium silt
Finer than 8 µm	Finer than fine silt
Finer than 4 µm	Finer than very fine silt
Finer than 2 µm	Finer than clay/colloids

2.2.3.7. Fish

Two tables, 'Fish' and 'FishMetals', contain fish data. The unique identifier for each fish (FishID) links records between the two tables. Table 'Fish' contains the following descriptive variables: species, race, sex, composite sample, spawning condition, length, weight, and age. Table 'FishMetals' contains concentrations of metals (e.g., Al, Cu, Cd, and Se) in whole bodies and individual tissues. The source files containing fish data were inconsistent in format and units, and missing details such as species and which tissues were analyzed for metals. We consulted other source files (e.g., reports and field notes) to fill in missing details required for analysis. Therefore, we used the following procedures to standardize the compilation of fish data:

1) Fish size and metal concentrations measured from fish carcasses (fish already dead when collected) were not included in the database, as decomposition would influence size and concentrations of metal;
2) Recaptured fish were assigned the measurements from their first capture that season;
3) Metal concentrations in tissue were converted to mg/kg dry weight (dw) whenever possible;
4) Sampling dates from field notes were preferred over those from analytical reports when they differed;
5) When sample date was reported as a range, fish were assigned:
    a) The sample date with the most records of catches, or
    b) The earliest sample date if there was an equal number of catches on multiple days;
6) Fish ages were reported in many different ways in the source files. Thus, fish ages (in years) were standardized as the following:
    a) If a file reported that age was not determined or that age could not be determined because fish scales were resorbed, ND was used;
    b) If age was reported as <1 years, zero was used;
    c) Where age was reported as X+, X was used;
    d) If age was reported as Xs+, where s was undefined in the source file, then age was reported as only X in the database;
    e) If the Gilbert-Rich age classification scheme was used in the source file, the total age was input into the age column and the subscript (denoting the age when the fish went to sea for the first time), was retained in its own column; and
    f) If the file reported an age of 0 years or and age class of either 0, fry, or juvenile, making sexing of the fish not possible, then sex was defined as immature.

2.2.3.8. Benthic invertebrates

Tables ‘InvertebrateSpecies’ and ‘InvertebrateMetals’ contain benthic invertebrate data. Table ‘InvertebrateSpecies’ contains taxonomy (SpeciesID) and abundance data. Table ‘InvertebrateMetals’ contains concentrations of metals (e.g., Al, Cu, Cd, and Se) in samples of pooled invertebrates. Field replicates were taken from different habitats in the same general vicinity to capture the diversity of the invertebrates in a given location. Thus, we included them in the database by 1) summing the field replicates for abundance, and 2) reported replicates as individual replicates for a given time and place.

2.2.3.9. Plankton

Table ‘Plankton’ includes all the abundance data for plankton. Many source files mention that UID flagellates were observed but not counted in samples. We did not include these records in the database since they were missing abundance values. There were no data on the concentration of metals in plankton.

2.2.3.10. Amphibians

Table ‘TadpoleMetals’ contains all the amphibian data, including species, life stage, length, and concentrations of metals (e.g., Al, Cu, Cd, and Se) in pooled samples.

3. Data analysis

3.1.1. Sample sites and sampling intensity

We mapped the sample sites and sampling intensity of the sites using ArcMap 10.5.1 [6], lake and river shapefiles from the Government of British Columbia [7,8], and world imagery and province boundary shapefiles from Esri Inc. [9,10]. Sampling intensity is the number of sampling events per sample site. This approach is a fairer way to visually compare among sites than by the number of samples collected at each site. For examples, 100 samples could have been collected on one occasion from a sample site, while one sample was collected for 100 days at another sample site.

3.1.2. General analysis of water, sediment, and biota

All data were analyzed in R v. 3.5.2 [11] and RStudio v. 1.1.463 [12]. Each data set was summarized to determine which waterbodies and variables (e.g., metals) were adequately sampled for further analysis. Formal inferential hypothesis testing required testing data distributions both visually and formally. Visual analysis included plotting frequency histograms for each variable of interest. Parametric assumption testing tested for sample normality and homogeneity of variance using Shapiro-Wilk and Bartlett tests, respectively. Parametric tests were used whenever test assumptions were met, while non-parametric tests were used if transformations (e.g., log) to meet test assumptions failed or sampling bias was too great. Statistical significance was set a priori at $p < 0.05$. In many if not most cases, inferential analysis was not possible owing to missing data, inappropriate sampling regimes, or egregious violations of statistical assumptions. In those cases, analyses were strictly descriptive and qualitative in nature.

3.1.3. Water

3.1.3.1. Limnology

Limnological variables analyzed included pH, water hardness, dissolved organic matter (DOC), total suspended solids (TSS), turbidity, total dissolved solids (TDS), conductivity, and phosphorus (P).

Pre- and post-breach values of each variable were compared using a Wilcoxon rank sum test with continuity correction. In addition, individual values for each variable were graphed as the number of days from breach (day 0) and visually examined for temporal trends and compared to the BCENV WQG for total P (5–15 μg/L, inclusive) [13].

3.1.3.2. Metals

The function 'censummary' and 'censtats' from the R package 'NADA' [14] was used to descriptively analyze the dataset for censorship of samples in order to determine which variables had sufficient data for further analysis. Variables with more than 50% of their data left-censored (i.e., values at or below an analytical detection limit) were modeled using a Kaplan-Meier estimate. Pre- and post-breach concentrations were compared using a Kruskal-Wallis rank sum test followed by a pairwise comparisons using Tukey and Kramer (Nemenyi) test with Tukey-Dist approximation for independent samples in the R package 'PMCMR' [15]. Individual values for each metal and waterbody were graphed as the number of days from breach (day 0) and visually examined for temporal trends and compared to the BCENV's WQG for dissolved Al (0.05 mg/L at pH $\geq$ 6.5), total As (5 mg/L), and total Cu (0.007 mg/L at water hardness of 57 mg/L $CaCO_3$) [13]. We chose to compare individual Cu concentrations to the WQG for total Cu at the average water harness of Quesnel Lake prior to the breach (57 mg/L as $CaCO_3$) because the analysis of water metal concentrations focused primarily on Quesnel Lake.

3.1.4. Sediment

A Wilcoxon rank sum test was used to compare metals concentrations in sediment pre- and post-breach. We graphed individual metal concentrations over time and visually examined them for temporal trends and compared them to BCENV's SQG for Se (2 mg/kg dw) [16].

3.1.5. Fish

A one-way ANOVA with a post-hoc Tukey test was used to compare metal (Al, As, Cu, and Se) and major ion (Ca and Na) concentrations in tissues (carcass, gills, gonad, liver, and muscle) of Rainbow Trout and Sockeye Salmon from Quesnel Lake and Polley Lake.

3.1.6. Benthic invertebrates

We limited the analysis of benthic invertebrate community to family, the lowest taxonomic level represented at most sites. In addition, we converted species abundance to presence/absence data to limit data assumptions surrounding unequal sampling effort. We ran a detrended correspondence analysis ('decorana' function in R package 'Vegan' [17]) and calculated Shannon's diversity index values on the presence-absence data pre- and post-breach. For Shannon's diversity index, we could not calculate either evenness or abundance because the data simply are not comparable among sites.

3.1.7. Plankton

As with benthic invertebrate communities, we limited the analysis of plankton community to family, the lowest taxonomic level represented at most sites and converted species abundance to presence/absence (see subsection 3.1.6). Using the package Vegan in R, we conducted a diversity—Shannon's diversity index—and species richness analysis on the presence-absence data pre- and post-breach [11,17,18]. With such a limited dataset, we could not calculate evenness or abundance.

3.1.8. Amphibians

We did not examine amphibians because there were no data for amphibians pre-breach or in waterbodies of interest—Quesnel Lake, Polley Lake, and Hazeltine Creek.

4. Results

4.1. Sample sites and sampling intensity

Data analyzed were collected from 210 sample sites (Fig. 3). Sampling intensity—number of sampling events not number of samples—varied greatly by waterbody, sample site, and sampled media (i.e., water, sediment, and biota). Figures 4 and 5 depicts the sampling intensity within the most heavily sampled area surrounding the MPMC and Quesnel Lake, while Appendix 2 contains details for each sample site. Although 19 and 18 waterbodies were sampled pre- and post-breach, respectively, sampling was biased toward the same few waterbodies—Quesnel Lake, Polley Lake, Hazeltine Creek—pre- and post-breach. The number of sampling sites increased post-breach in Quesnel Lake (especially near the mouth of Hazeltine Creek), Polley Lake, Hazeltine Creek, and Edney Creek. However, the number of sampling sites in regional reference waterbodies and reference sites within the North and East Arms of Quesnel Lake decreased post-breach. Our analysis is limited to pre- and post-breach comparisons within a given waterbody, as there are not adequately sampled regional references to compare with potentially affected waterbodies. Fewer than half of the sites (45%) having been sampled more than 3 times (Appendix 2). Water (limnology and metals) was sampled more often and at more sites than sediment and biota (Fig. 4 and 5). It should be noted that post breach is not the same as post remediation. The difference in the means presented in this report likely represents the impact during the immediate aftermath only, since the data from the immediate aftermath of the spill significantly influences the pre-post breach comparison, and no comparison was done between pre-breach and post remediation. That being said, while many parameters spiked after the breach, followed by a reduction during remediation, there are a few parameters that remain slightly higher than pre-breach conditions, but still meet relevant guidelines. This will be discussed in more detail in the following sections.

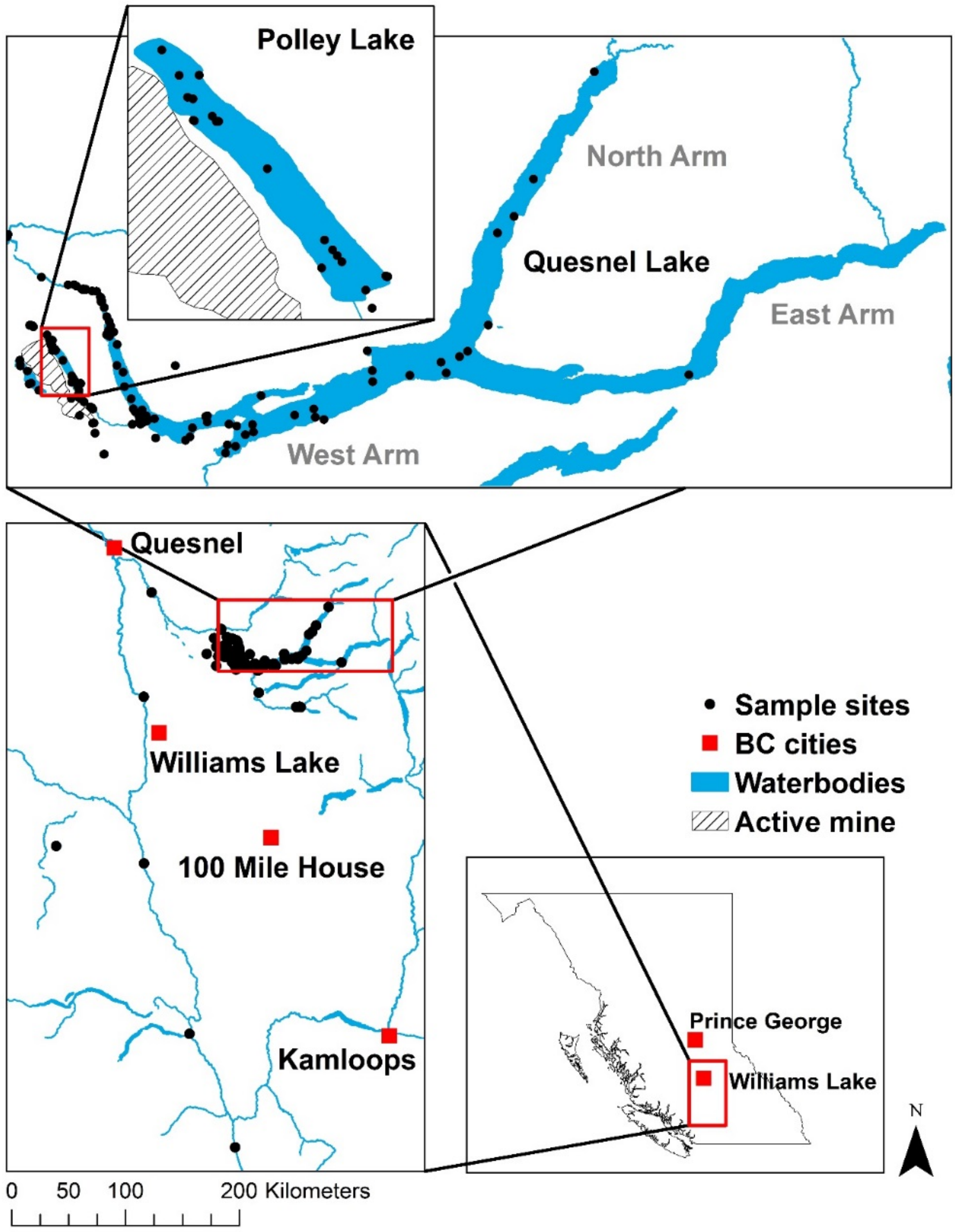

Figure 3. Sample sites identified for water, sediment, and biota data analyzed from database.

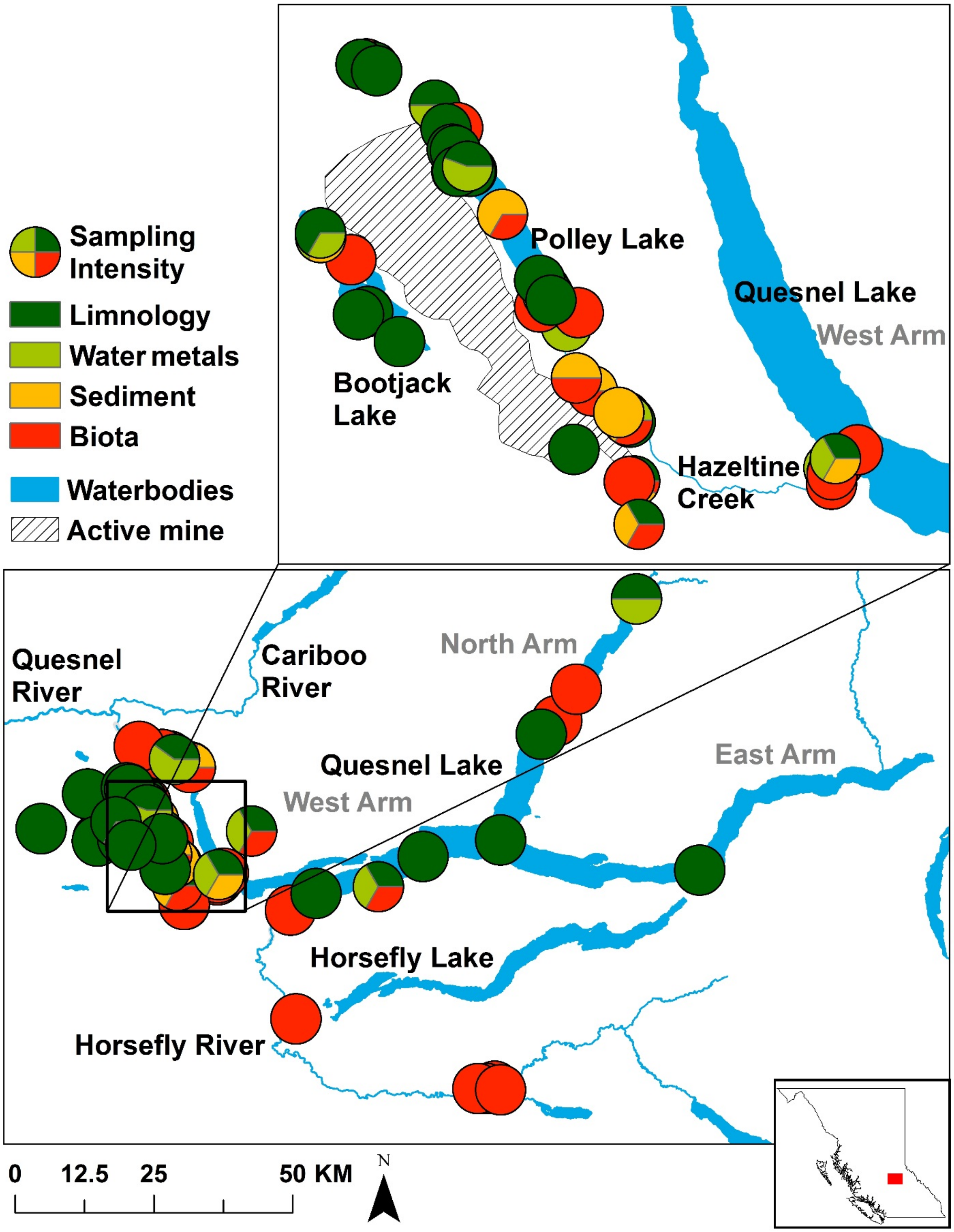

Figure 4. Sampling intensity (number of sampling events not number of samples) of water (limnology and metals), sediment, and biota by waterbody pre-breach.

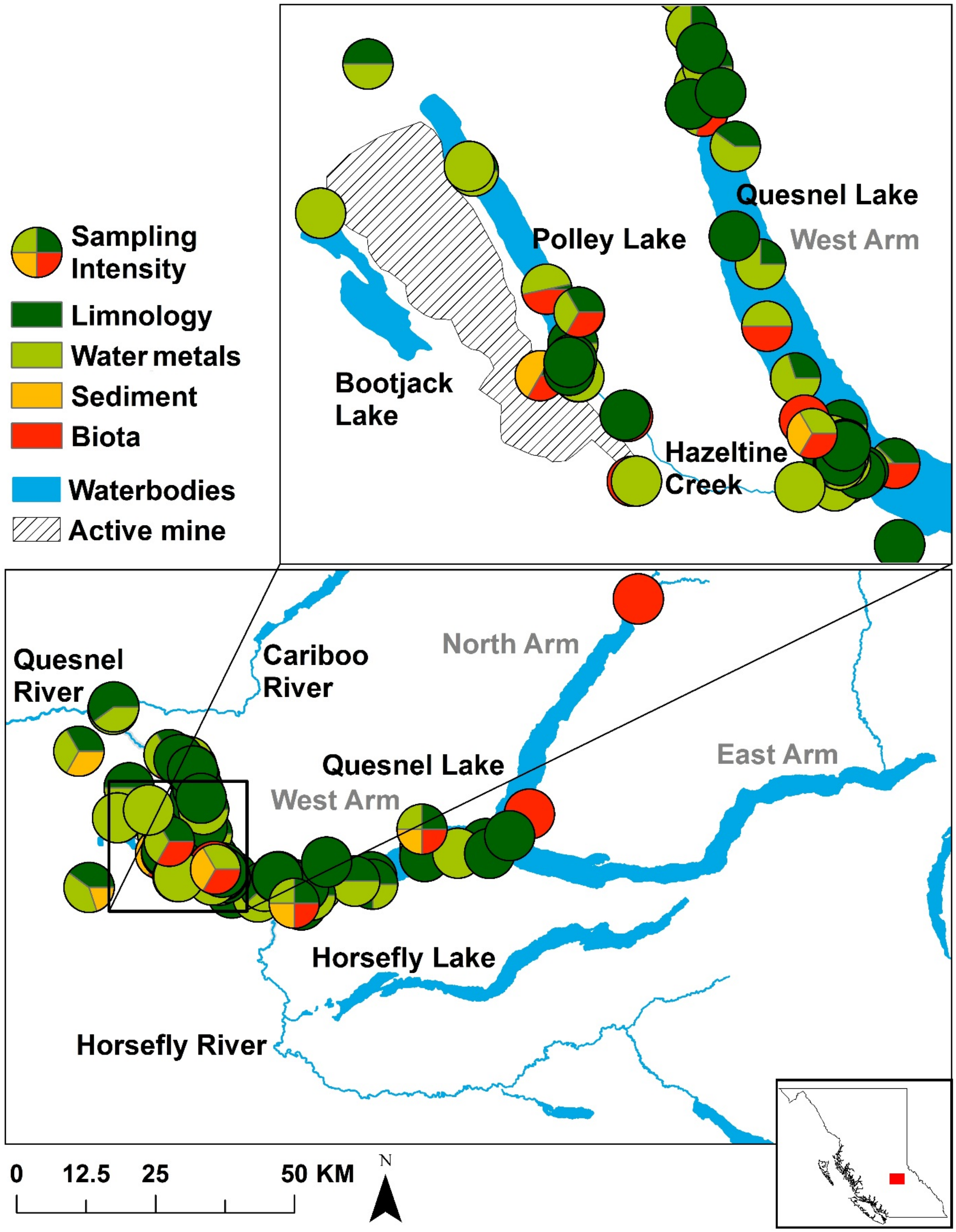

Figure 5. Sampling intensity (number of sampling events not number of samples) of water (limnology and metals), sediment, and biota by waterbody post-breach.

4.2. Water

4.2.1. Limnology

Quesnel Lake, Polley Lake, Hazeltine Creek, Edney Creek, and Quesnel River have been adequately sampled pre- and post-breach to allow for a temporal comparison of limnological variables (pH, conductivity, water hardness, DOC, TSS, turbidity, TDS, and P; Fig. 4 and 5). Quesnel River was sampled the least out of the five waterbodies resulting in small sample sizes that prevented the analysis of DOC. Quesnel Lake, Polley Lake, and Hazeltine Creek were affected by the breach, as the means of all limnological variables differed post-breach for Quesnel Lake ($p < 0.05$), and all variables, but DOC, for Polley Lake and Hazeltine Creek ($p > 0.05$; Fig. 6–8). Only TDS were elevated in Edney Creek post-breach ($p < 0.05$; Fig. 9), and no variable differed post-breach in Quesnel River ($p > 0.05$; Fig. 10). Temporal trends are visible in the limnological data of each waterbody (Fig. 11–15). In Quesnel Lake, conductivity, water hardness, TSS, turbidity, and P levels were noticeably elevated at the time of the breach and decreased quickly afterwards, as well as turbidity in Polley Lake and turbidity and TSS in Hazeltine Creek (Fig. 11–13). The water hardness, TDS, and P levels are markedly elevated at the time of the breach in Polley Lake and Hazeltine Creek and have remained so, as well as conductivity in Hazeltine Creek (Fig. 12 and 13). There are a few high values of P in Quesnel River and P and TSS in Edney Creek at the time of the breach (Fig. 14 and 15). All five waterbodies exceeded the WQG for total P (5–15 µg/L, inclusive) by as much as 20 times in Quesnel Lake [13].

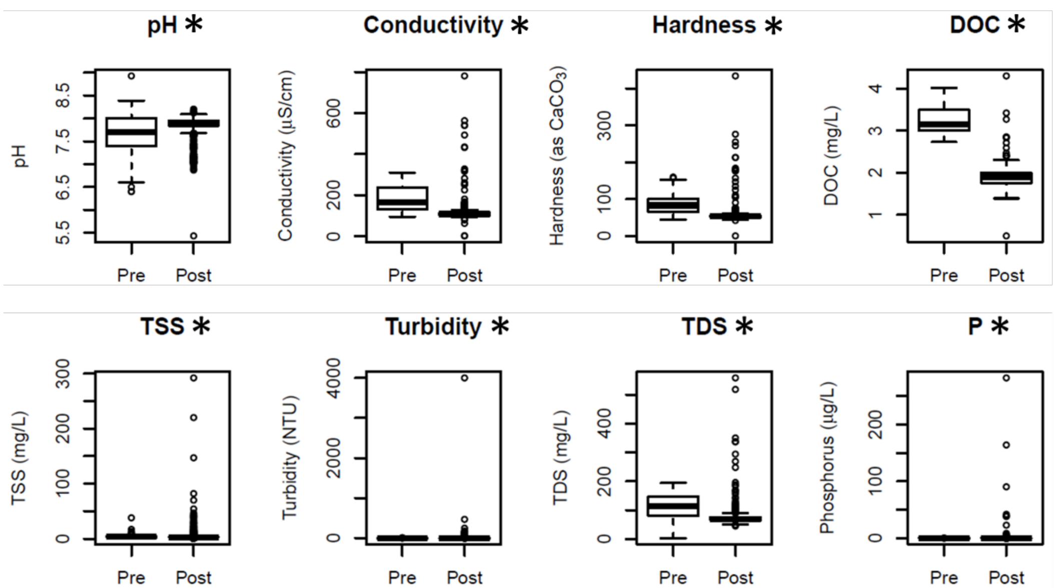

Figure 6. Limnological variables of Quesnel Lake pre-breach (Pre) and post-breach (Post). Variables are pH, conductivity, hardness (mg/L as $CaCO_3$), dissolved organic carbon (DOC), total suspended solids (TSS), turbidity, total dissolved solids (TDS), and total phosphorus (P). An asterisk (*) next to the variable represents a difference ($p < 0.05$) between pre- and post-breach means.

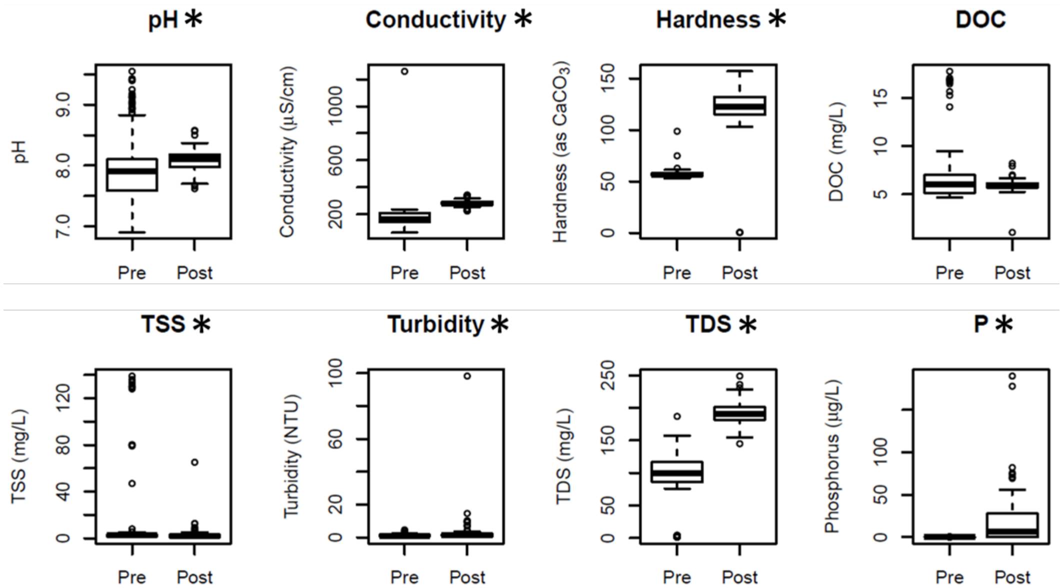

Figure 7. Limnological variables of Polley Lake pre-breach (Pre) and post-breach (Post). Variables are pH, conductivity, hardness (mg/L as $CaCO_3$), dissolved organic carbon (DOC), total suspended solids (TSS), turbidity, total dissolved solids (TDS), and total phosphorus (P). An asterisk (*) next to the variable represents a difference ($p < 0.05$) between pre- and post-breach means.

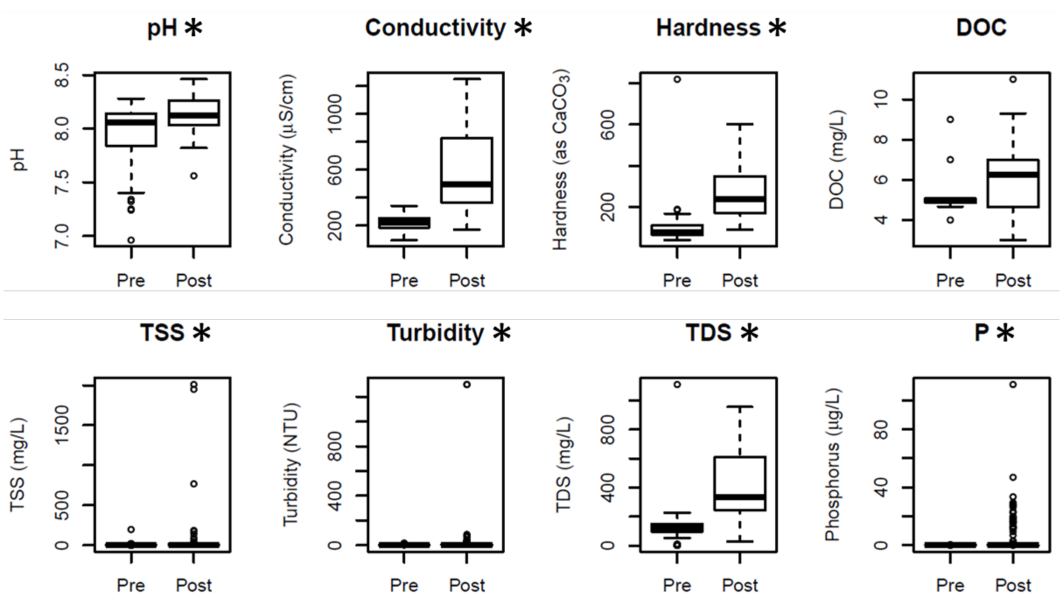

Figure 8. Limnological variables of Hazeltine Creek pre-breach (Pre) and post-breach (Post). Variables are pH, conductivity, hardness (mg/L as $CaCO_3$), dissolved organic carbon (DOC), total suspended solids (TSS), turbidity, total dissolved solids (TDS), and total phosphorus (P). An asterisk (*) next to the variable represents a difference ($p < 0.05$) between pre- and post-breach means.

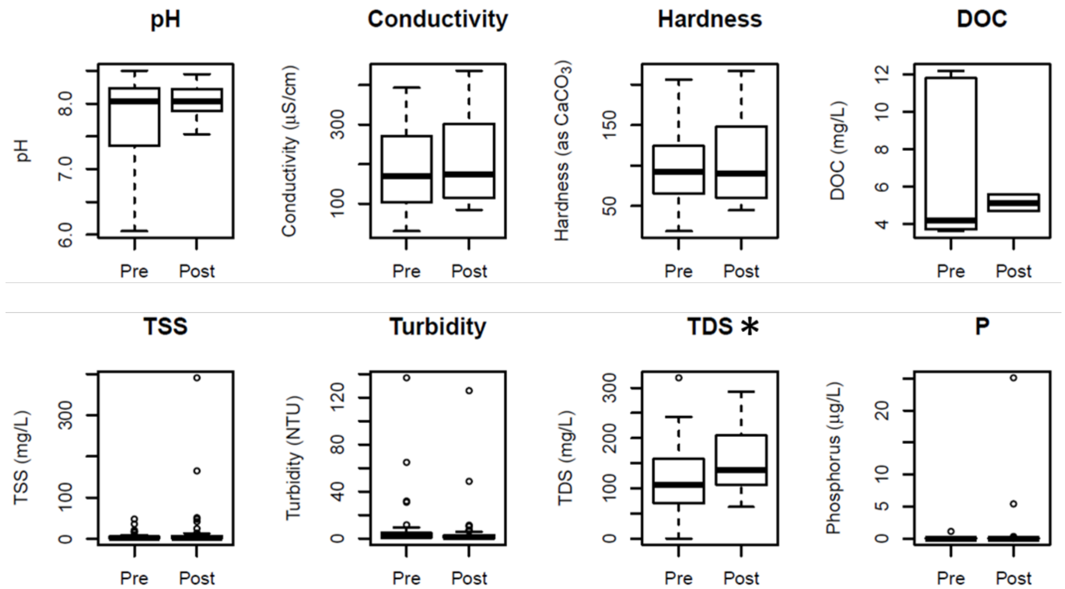

Figure 9. Limnological variables of Edney Creek pre-breach (Pre) and post-breach (Post). Variables are pH, conductivity, hardness (mg/L as $CaCO_3$), dissolved organic carbon (DOC), total suspended solids (TSS), turbidity, total dissolved solids (TDS), and total phosphorus (P). An asterisk (*) next to the variable represents a difference ($p < 0.05$) between pre- and post-breach means.

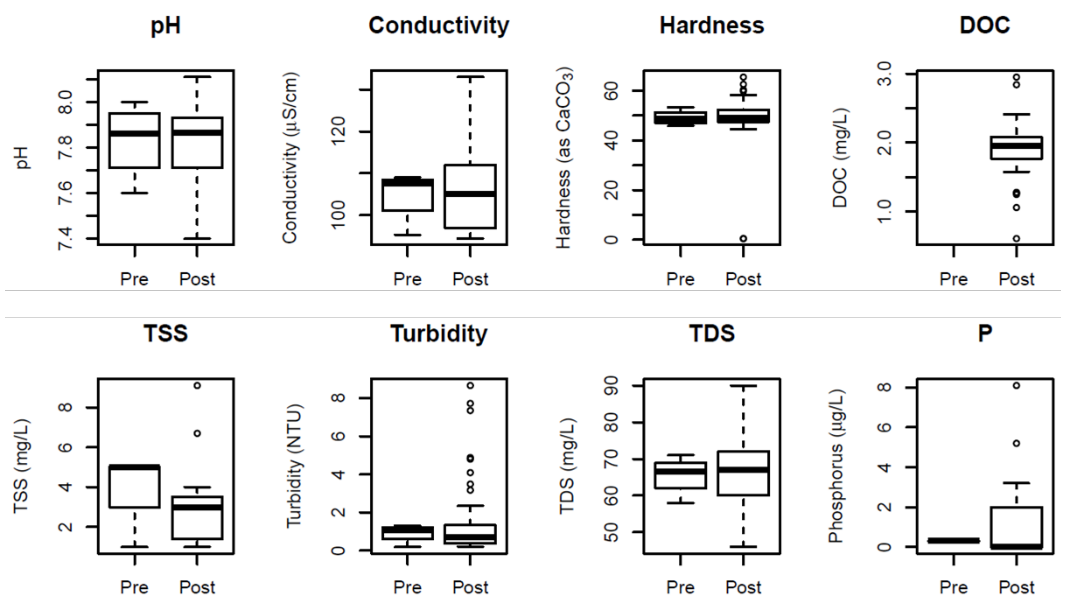

Figure 10. Limnological variables of Quesnel River pre-breach (Pre) and post-breach (Post). Variables are pH, conductivity, hardness (mg/L as $CaCO_3$), dissolved organic carbon (DOC), total suspended solids (TSS), turbidity, total dissolved solids (TDS), and total phosphorus (P).An asterisk (*) next to the variable represents a difference ($p < 0.05$) between pre- and post-breach means.

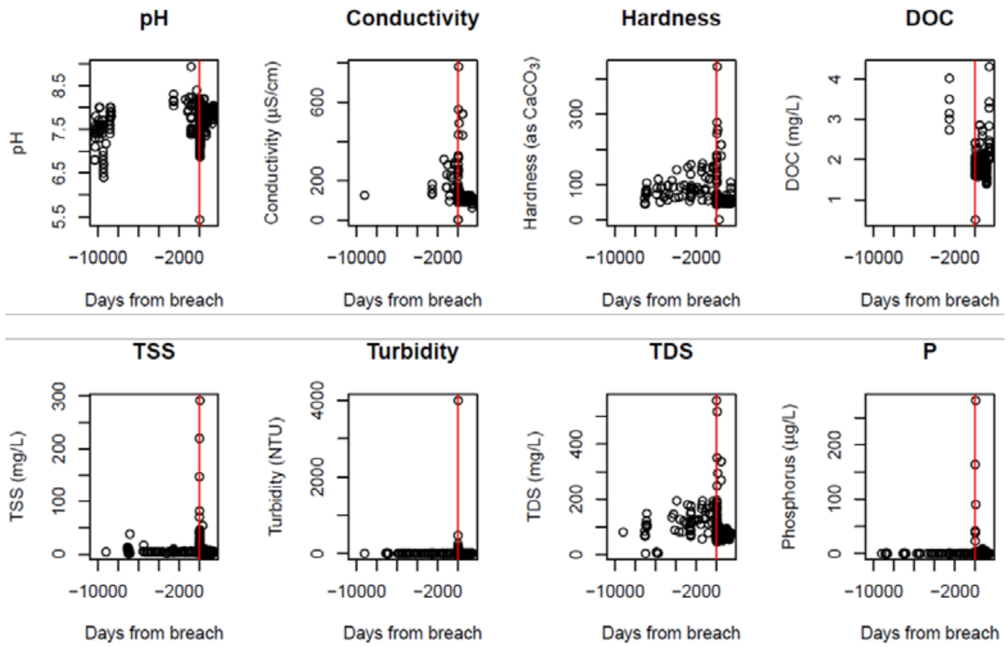

Figure 11. Limnological variables of Quesnel Lake by number of days from breach. Variables are pH, conductivity, hardness (mg/L as $CaCO_3$), dissolved organic carbon (DOC), total suspended solids (TSS), turbidity, total dissolved solids (TDS), and total phosphorus (P). The vertical red line represents the breach on 4 August 2014 (0 days).

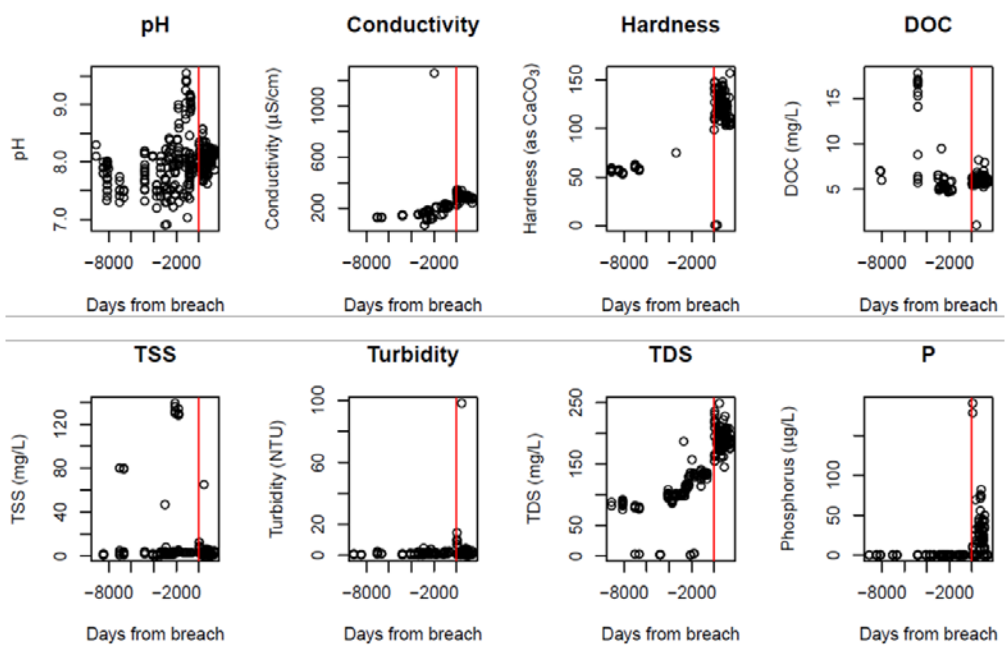

Figure 12. Limnological variables of Polley Lake by number of days from breach. Variables are pH, conductivity, hardness (mg/L as $CaCO_3$), dissolved organic carbon (DOC), total suspended solids (TSS), turbidity, total dissolved solids (TDS), and total phosphorus (P). The vertical red line represents the breach on 4 August 2014 (0 days).

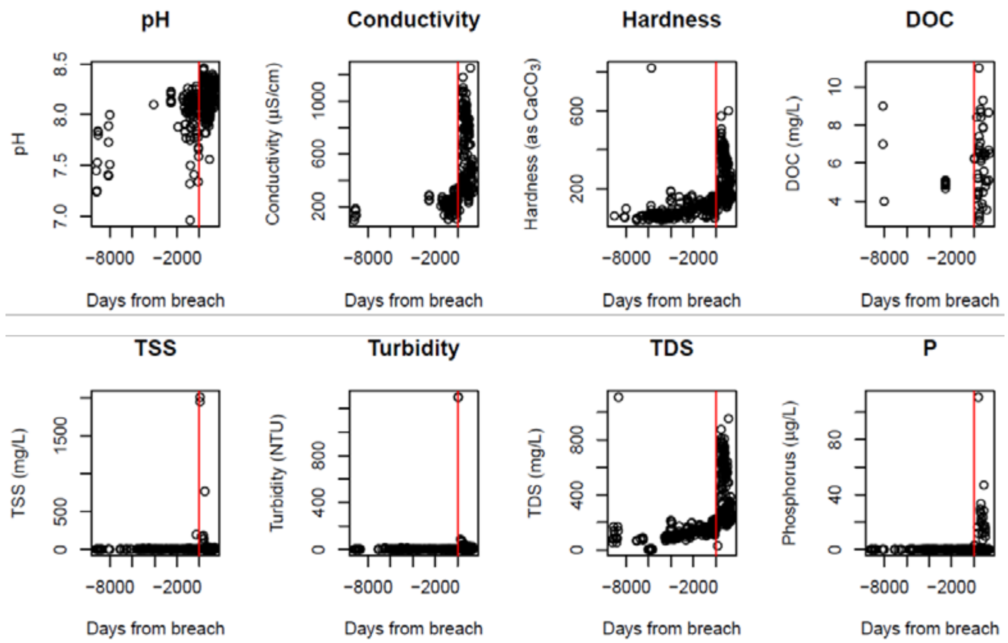

Figure 13. Limnological variables of Hazeltine Creek by number of days from breach. Variables are pH, conductivity, hardness (mg/L as $CaCO_3$), dissolved organic carbon (DOC), total suspended solids (TSS), turbidity, total dissolved solids (TDS), and total phosphorus (P). The vertical red line represents the breach on 4 August 2014 (0 days).

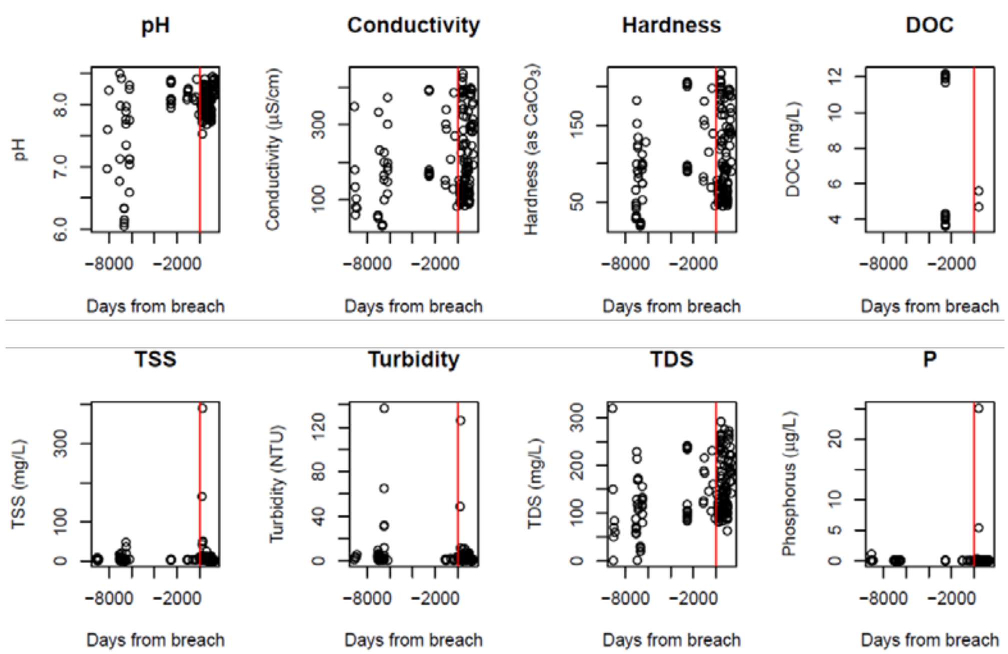

Figure 14. Limnological variables of Edney Creek by number of days from breach. Variables are pH, conductivity, hardness (mg/L as $CaCO_3$), dissolved organic carbon (DOC), total suspended solids (TSS), turbidity, total dissolved solids (TDS), and total phosphorus (P). The vertical red line represents the breach on 4 August 2014 (0 days).

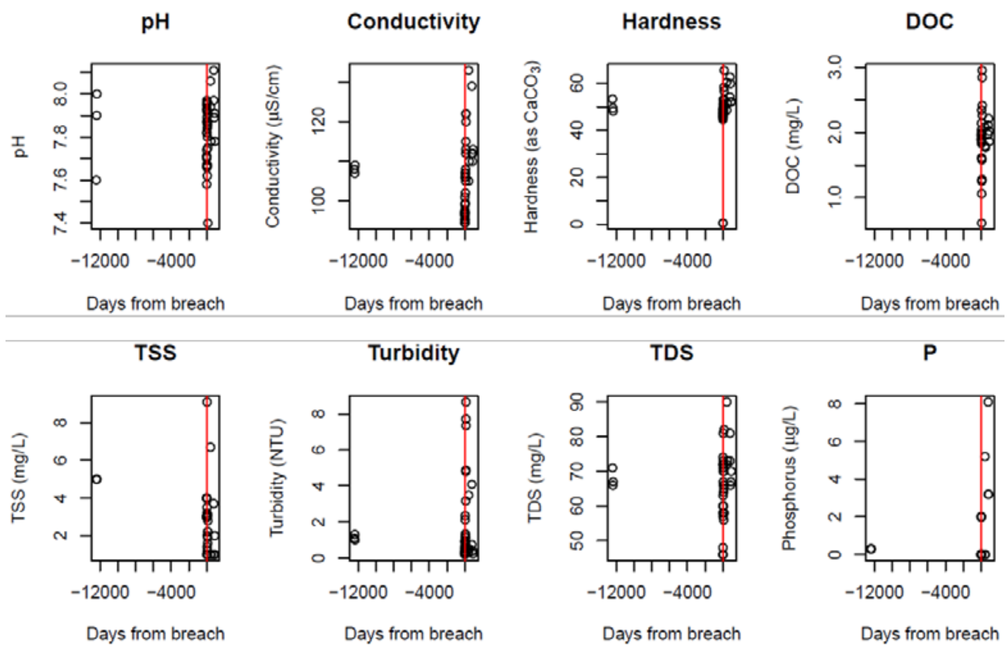

Figure 15. Limnological variables of Quesnel River by number of days from breach. Variables are pH, conductivity, hardness (mg/L as $CaCO_3$), dissolved organic carbon (DOC), total suspended solids (TSS), turbidity, total dissolved solids (TDS), and total phosphorus (P). The vertical red line represents the breach on 4 August 2014 (0 days).

4.2.2. Metals

Water sampling for determining metal concentrations has been uneven among the various water bodies represented in the database (Table 2, Fig. 4 and 5). The only waterbodies that have been adequately sampled to allow for a comparison between pre- and post-breach metal concentrations are Quesnel Lake, Polley Lake, Edney Creek, and Hazeltine Creek. Many of the water metals data are left-censored. Only Al, As, and Cu have sufficient pre-breach data (<50% of samples left-censored) for the subsequent analysis (Table 3). The rest of the dataset contained metal concentrations that were at or below the analytical detection limits of the instruments used to analyze the samples. Pre-breach mean total Cu concentration in Quesnel Lake, Polley Lake, Hazeltine Creek, and Edney Creek were below WQG (0.007 mg/L for water hardness of 57 mg/L as $CaCO_3$). Dissolved Al in Hazeltine Creek was at WQG (0.05 mg/L at pH $\geq$ 6.5) and at 60% and 50% of the WQG in Quesnel Lake and Edney Creek (Table 4) [13]. Post-breach total Cu concentrations increased post-breech exceeding the WQG 1.4 times in Quesnel Lake and 2.9 times in Hazeltine Creek (Table 5) [13]. Although total Cu concentrations in Polley Lake and Edney Creek did not exceed WQG, the total Cu concentrations increased from 29% and 14% to 86% and 57% of the WQG, respectively (Table 5). Dissolved Al concentrations post-breach were 1.2 times the WQG in Edney Creek and at 70% of the WQG in Hazeltine Creek. Total As concentrations remained below WQG pre- and post-breach. However, there was a slight increase in concentrations in Polley Lake and Hazeltine Creek and a small decrease in Quesnel Lake concentrations post-breach (Tables 4 and 5). Thus, As was not analyzed further in the water analysis.

Table 2. Water quality sampling for metals analysis pre- and post-breach. The bolded waterbodies are those with adequate sampling pre- and post-breach to analyze for metals. Non-bolded waterbodies are reference streams/lakes.

Waterbody	Total samples	Pre-breach	Post-breach
6K Creek	3	3	0
Blackwater Creek	2	0	2
Bootjack Creek	1	1	0
Bootjack Lake	127	126	1
Cariboo River	42	0	42
Cedar Creek	8	0	8
Clearbrook Creek	2	0	2
Clearwater River	2	0	2
East Side Pond	2	0	2
Edney Creek	334	116	218
Fish Lake	6	6	0
Frypan Lake	6	0	6
Gavin Lake	8	0	8
Hazeltine Creek	942	556	386
Horsefly River	27	3	24
Kay Lake Creek	1	1	0
Little Lake	1	0	1
Mine Drainage Creek	1	1	0
Morehead Creek	3	3	0
Mt. Polley Mining Corp.	18	0	18
North Dump Creek	1	1	0
PAR Wetland	8	0	8
Polley Flats	46	0	46
Polley Lake	440	185	255
Pond 33	4	0	4
Quesnel Lake	4136	141	3995
Quesnel River	89	3	86
Rat Creek	2	0	2
Taseko River	1	1	0
Tasse Creek	2	0	2
Unknown waterbody	10	0	10
Unnamed Creek	2	0	2
West Duck Pond	4	0	4
Whiffle Creek	9	5	4
Winkley Creek	2	0	2

Table 3. The degree of censorship in the pre-breach water-metals dataset. The dataset includes both filtered water samples (n = 465) and unfiltered water samples (n = 538). Those metals having less than 50% of samples left-censored (bolded) were included in the comparison between pre- and post-breach metal concentrations. The data have not been broken down by site; rather, this is the entire pre-breach dataset.

Metal	Type	Censorship (%)
Al	Dissolved	12.8
	Total	3.2
As	Dissolved	7.5
	Total	7.3
Cd	Dissolved	87
	Total	84
Cr	Dissolved	80.2
	Total	67.3
Co	Dissolved	76.2
	Total	63.3
Cu	Dissolved	3.7
	Total	2.8
Ni	Dissolved	76.2
	Total	65.5
Pb	Dissolved	73.2
	Total	59.9
Se	Dissolved	70.5
	Total	71.3
Sn	Dissolved	77.2
	Total	79.3
V	Dissolved	60.3
	Total	53.4
Zn	Dissolved	65.9
	Total	61.7

Table 4. Pre-breach analysis of dissolved and total Al, As, and Cu by waterbody. Kaplan-Meier estimates were used to account for left-censored data and compared to BCENV WQG for Al (0.05 mg/L at pH ≥ 6.5), As (0.05 mg/L), and Cu (0.007 mg/L Cu at water hardness of 57 mg/L as $CaCO_3$) [13]. Concentrations at or above the WQG are bolded. There are currently no guidelines for total Al and dissolved As and Cu [13].

Waterbody	**Metal**	**Sample type**	**Median (mg/L)**	**Mean (mg/L)**	**SD (mg/L)**	**n**	**WQG (mg/L)**
Quesnel Lake	Al	Dissolved	0.02	0.03	0.03	47	0.05[b]
		Total	0.04	0.07	0.06	54	—
	As	Dissolved	0.0007	0.0007	0.0002	47	—
		Total	0.0007	0.0007	0.0002	54	0.005[c]
	Cu	Dissolved	0.002	0.002	0.001	47	—
		Total	0.002	0.002	0.001	54	≤0.007[b]
Polley Lake	Al	Dissolved[a]	0.005	0.001	0.002	10	0.05[b]
		Total	0.005	0.009	0.01	21	—
	As	Dissolved[a]	0.0003	0.0003	<0.0001	10	—
		Total[a]	0.0004	0.0004	<0.0001	21	0.005[c]
	Cu	Dissolved	0.002	0.002	0.0006	10	—
		Total	0.002	0.002	0.001	21	≤0.007[b]
Hazeltine Creek	Al	Dissolved	0.02	**0.05**	0.06	219	0.05[b]
		Total	0.06	0.1	0.11	232	—
	As	Dissolved	0.0005	0.0005	0.0002	219	—
		Total	0.0005	0.0005	0.0002	232	0.005[c]
	Cu	Dissolved	0.002	0.003	0.005	219	—
		Total	0.003	0.003	0.005	232	≤0.007[b]
Edney Creek	Al	Dissolved	0.006	0.02	0.04	9	0.05[b]
		Total	0.02	0.04	0.05	25	—
	As	Dissolved	0.001	0.001	0.0006	9	—
		Total	0.0009	0.001	0.0005	25	0.005[c]
	Cu	Dissolved	0.001	0.002	0.0009	9	—
		Total	0.001	0.001	0.0009	25	≤0.007[b]

a. Approached or exceeded 50% threshold of censored data; interpret with caution.
b. Long-term average WQG
c. Maximum WQG

Table 5. Post-breach analysis of dissolved and total Al, As, and Cu by waterbody. Kaplan-Meier estimates were used to account for left-censored data and compared to BCENV WQG for Al (0.05 mg/L at pH ≥ 6.5), As (0.05 mg/L), and Cu (0.007 mg/L Cu at water hardness of 57 mg/L as $CaCO_3$) [13]. Concentrations at or above the WQG are bolded. There are currently no guidelines for total Al and dissolved As and Cu [13].

Waterbody	**Metal**	**Sample type**	**Median (mg/L)**	**Mean (mg/L)**	**SD (mg/L)**	**n**	**WQG (mg/L)**
Quesnel Lake	Al	Dissolved	0.008	0.009	0.01	1991	0.05[a]
		Total	0.03	0.38	4.8	1991	—
	As	Dissolved	0.0001	0.0003	0.003	1991	—
		Total	0.0001	0.0001	0.0002	1991	0.005[b]
	Cu	Dissolved	0.0007	0.001	0.003	1991	—
		Total	0.001	**0.01**	0.21	1991	≤0.007[a]
Polley Lake	Al	Dissolved	0.003	0.004	0.003	123	0.05[a]
		Total	0.03	0.004	0.003	126	—
	As	Dissolved	0.0008	0.0009	0.0002	123	—
		Total	0.0009	0.0009	0.0003	126	0.005[b]
	Cu	Dissolved	0.003	0.003	0.001	123	—
		Total	0.004	0.006	0.013	126	≤0.007[a]
Hazeltine Creek	Al	Dissolved	0.019	0.035	0.04	193	0.05[a]
		Total	0.186	0.830	5.03	193	—
	As	Dissolved	0.0009	0.0009	0.003	193	—
		Total	0.001	0.001	0.002	193	0.005[b]
	Cu	Dissolved	0.008	0.009	0.005	193	—
		Total	0.01	**0.02**	0.05	193	≤0.007[a]
Edney Creek	Al	Dissolved	0.05	**0.06**	0.06	109	0.05[a]
		Total	0.11	0.24	0.65	109	—
	As	Dissolved	0.0009	0.001	0.001	109	—
		Total	0.001	0.001	0.001	109	0.005[b]
	Cu	Dissolved	0.003	0.003	0.002	109	—
		Total	0.004	0.004	0.005	109	≤0.007[a]

a. Long-term average WQG for freshwater aquatic life
b. Maximum WQG for freshwater aquatic life

4.2.2.1. Copper by region in Quesnel Lake

Pre-breach data are strongly biased on samples collected in the East Arm of Quesnel Lake, as opposed to the West Arm like post-breach data. The sampling bias alone makes interpreting the data difficult. Pre-breach the Cu concentrations were low (0.5–2.3 µg/L) in all areas of Quesnel Lake, and there were no significant Cu concentration differences among the three arms ($\chi^2 = 4.30$, df = 2, p = 0.12; Fig. 16). There was a marginal significant difference in Cu concentration between post-breach Cu concentrations from the East and West Arm (Nemenyi test, p = 0.07), however, the Middle Arm had higher Cu concentrations than both the East and West Arm (Nemenyi test, p = 0.02; Fig. 17). The mean Cu concentration in the Middle Arm was one order of magnitude higher (34.7 µg/L ± 46.4 SD) than those of the West Arm (3.6 µg/L ± 12.6 SD), which itself is an order of magnitude higher than those measured in the East Arm (0.5 µg/L ± <0.001 SD; although, n = 2). It is difficult to draw meaningful conclusions from the data with a tremendous sampling bias, small sample sizes (n = 2), and when SD is greater than the means.

Pre- to post-breach comparisons of Cu concentrations are impossible to interpret with confidence for the East and Middle Arms because of inadequate sample sizes. Dissolved Cu concentration in the West Arm appears higher post-breach (0.006 mg/L ± 0.017 SD) relative to pre-breach (0.002 mg/L ± 0.001 SD; Table 4 and 5). However, the SD of the post-breach data is approximately 3 times the mean, which seriously impairs our ability to interpret the mean. Additionally, the pre-beach data were based on a small sample size (n = 5), which also lead to substantial uncertainty in the analysis. Temporal trends in Cu concentrations were visible in the West Arm of Quesnel Lake. Both total and dissolved Cu concentrations spiked in the months following the breach (Fig. 18 and 19). Those concentrations have since dropped below the WQG (total Cu 0.007 mg/L at water hardness of 57 mg/L as $CaCO_3$) [13].

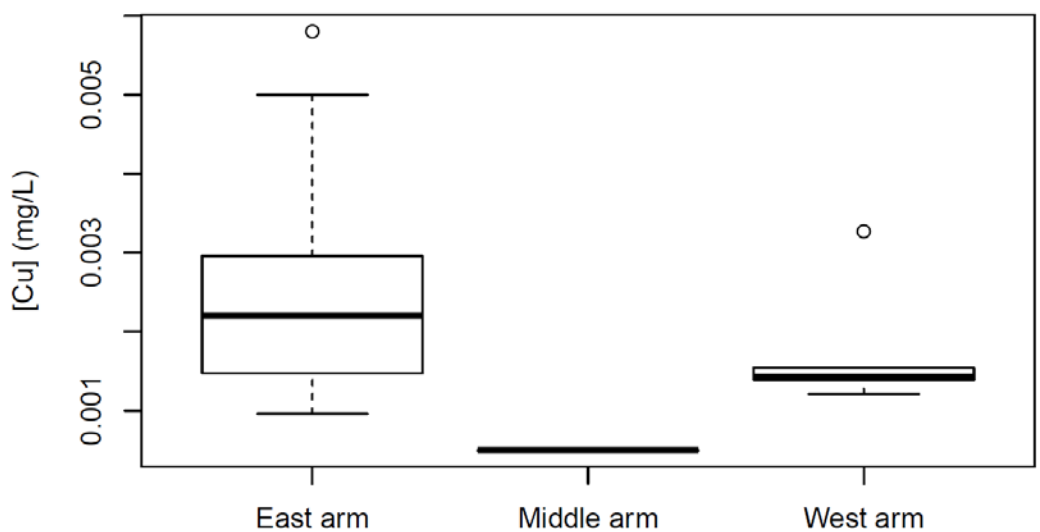

Figure 16. Pre-breach water Cu concentrations (mg/L) among three regions of Quesnel Lake. The regions are the East Arm, Middle Arm, and West Arm of Quesnel Lake.

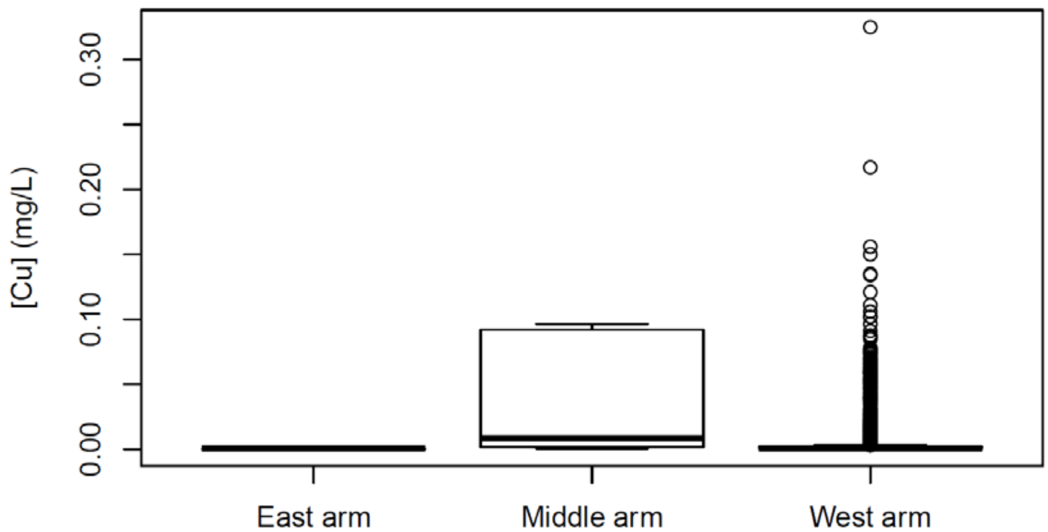

Figure 17. Post-breach water Cu concentrations (mg/L) among three regions of Quesnel Lake. The regions are the East Arm, Middle Arm, and West Arm of Quesnel Lake.

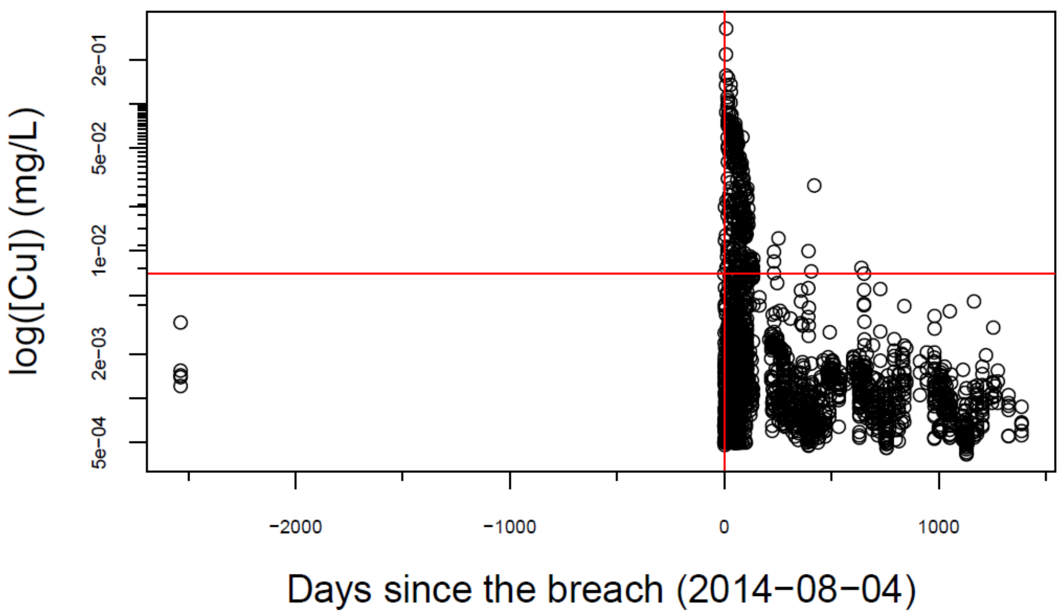

Figure 18. Total water Cu concentration (mg/L) in the West Arm of Quesnel Lake pre-breach (<0 days) and post-breach (≥0 days). The red vertical line denotes the breach on 4 August 2014, while the red horizontal line denotes the BCENV WQG for total Cu (0.007 mg/L at water hardness of ≤57 mg/L as $CaCO_3$) [13].

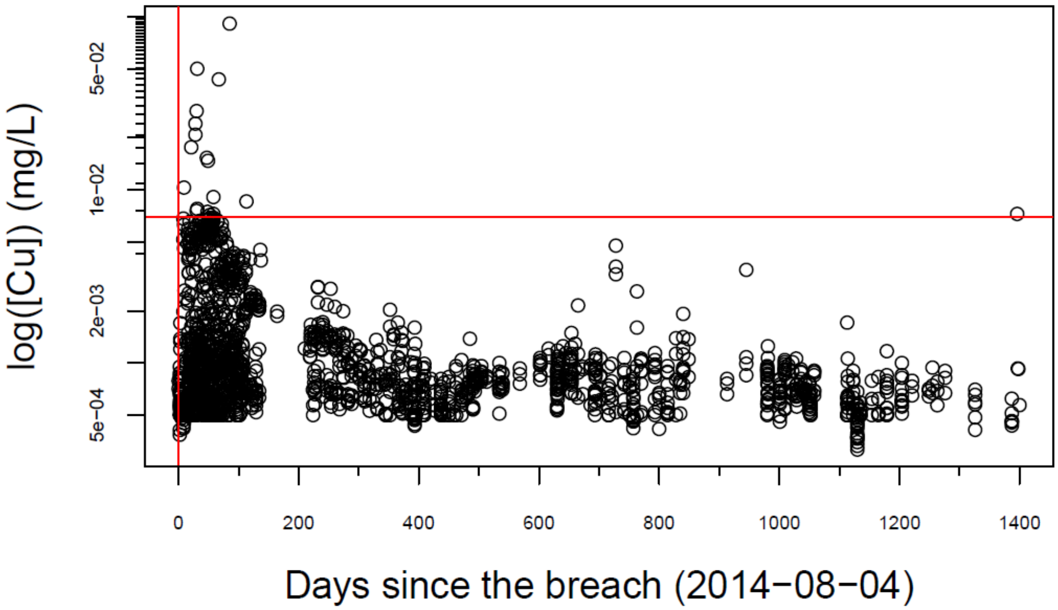

Figure 19. Dissolved water Cu concentration (mg/L) in the West Arm of Quesnel Lake pre-breach (<0 days) and post-breach (≥0 days). The red vertical line denotes the breach on 4 August 2014. As there currently is not a BCENV WQG for dissolved Cu, the red horizontal line denotes the BCENV WQG for total Cu (0.007 mg/L at water hardness of 57 mg/L as $CaCO_3$) [13].

4.2.2.2. Aluminum in the West Arm of Quesnel Lake

Pre- to post-breach comparisons of Al concentrations are impossible for the East and Middle Arms because of inadequate sample sizes. Temporal trends in Al concentrations are visible in the West Arm of Quesnel Lake. Both total and dissolved Al concentrations spiked in the days following the breach, exceeding WQG for dissolved Al (0.05 mg/L at pH ≥ 6.5; Fig. 20 and 21) [13]. However, the Al concentrations have decreased since then and currently remain below the WQG. Interestingly, most of the dissolved Al samples that were over the WQG occurred at about 50–75 m of depth (Fig. 22). Samples did not seem to exceed the WQG at the surface.

4.2.2.3. Copper and aluminum in Polley Lake

Total Cu was higher post-breach than pre-breach ($F_{(1,224)} = 53.27$, $p < 0.001$; Fig. 23), but did not differ by region (North and South Ends of Polley Lake; $F_{(1,224)} = 3.26$, $p = 0.07$). Post-breach total Cu concentration (0.006 mg/L) was near the WQG (total Cu 0.007 mg/L; Fig. 25) [13]. However, dissolved Cu was higher post-breach than pre-breach ($F_{(1,203)} = 55.19$, $p < 0.001$; Fig. 23) in the South End of the lake ($F_{(1,203)} = 10.37$, $p = 0.002$). Dissolved Cu still appears elevated years after the breach (Fig. 25).

Total Al was significantly higher post-breach than pre-breach ($F_{(1,205)} = 32.54$, $p < 0.001$; Fig. 24), but did not differ between the North and South Ends of the lake ($F_{(1,205)} = 0.69$, $p = 0.41$). Concentrations of total Al still remain elevated (Fig. 25). However, dissolved Al was not affected by either time ($F_{(1,192)}$ = 0.54, p = 0.46; Fig. 24) or region ($F_{(1,192)}$ = 1.02, p = 0.31). Dissolved Al concentrations generally fall below BCENV guideline (0.05 mg/L at pH ≥ 6.5; Fig. 25) [13].

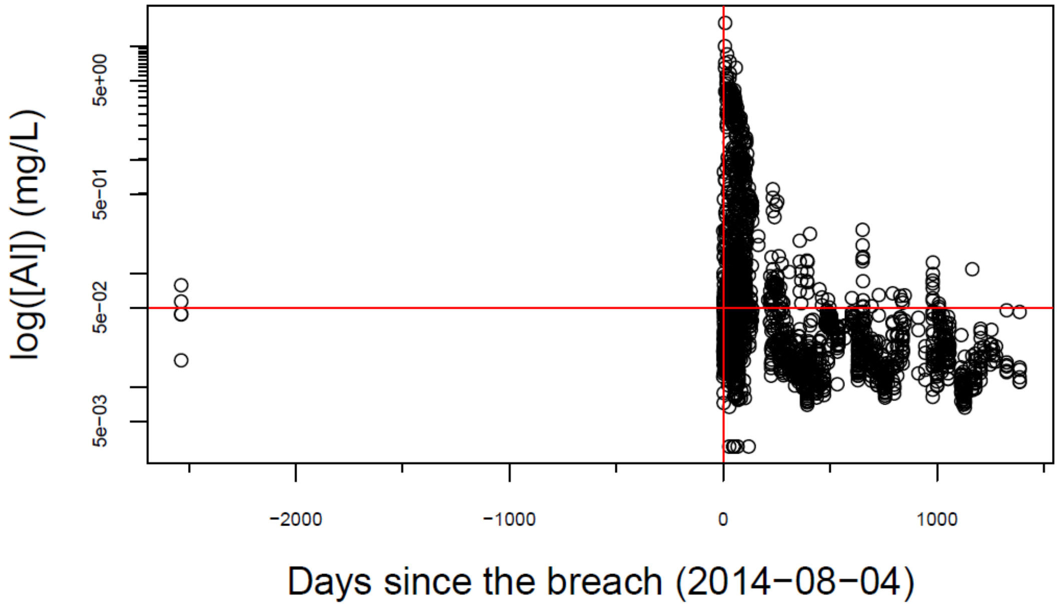

Figure 20. Total water Al concentration (mg/L) in the West Arm of Quesnel Lake pre-breach (<0 days) and post-breach (≥0 days). The red vertical line denotes the breach on 4 August 2014. As there currently is not a BCENV WQG for total Al, the red horizontal line denotes the BCENV WQG for dissolved Al (0.05 mg/L at pH ≥ 6.5) [13].

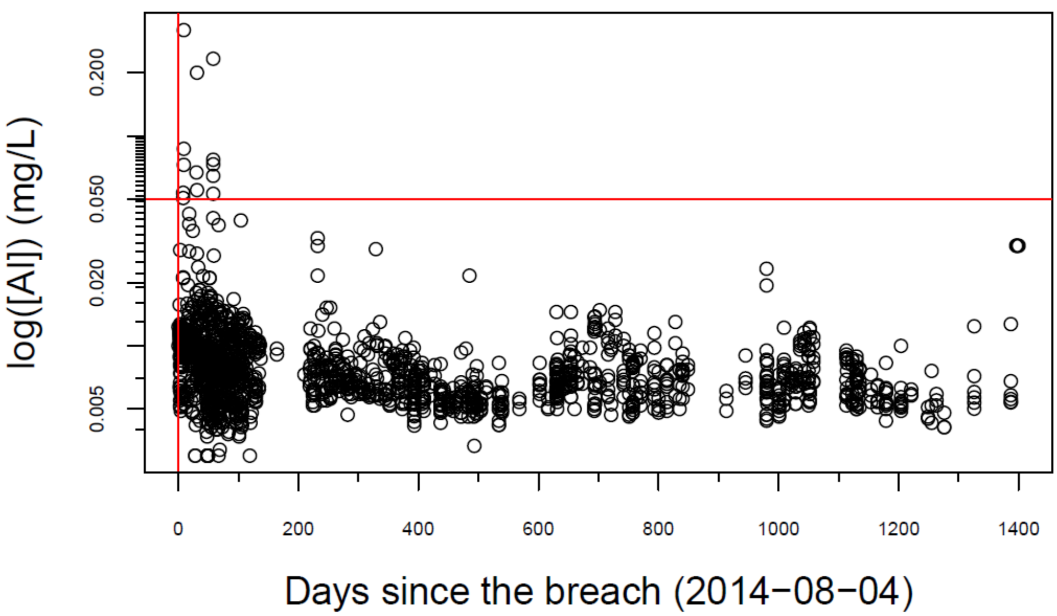

Figure 21. Dissolved water Al concentration (mg/L) in the West Arm of Quesnel Lake pre-breach (<0 days) and post-breach (≥0 days). The red vertical line denotes the breach on 4 August 2014, while the red horizontal line denotes the BCENV WQG for dissolved Al (0.05 mg/L at pH ≥ 6.5) [13].

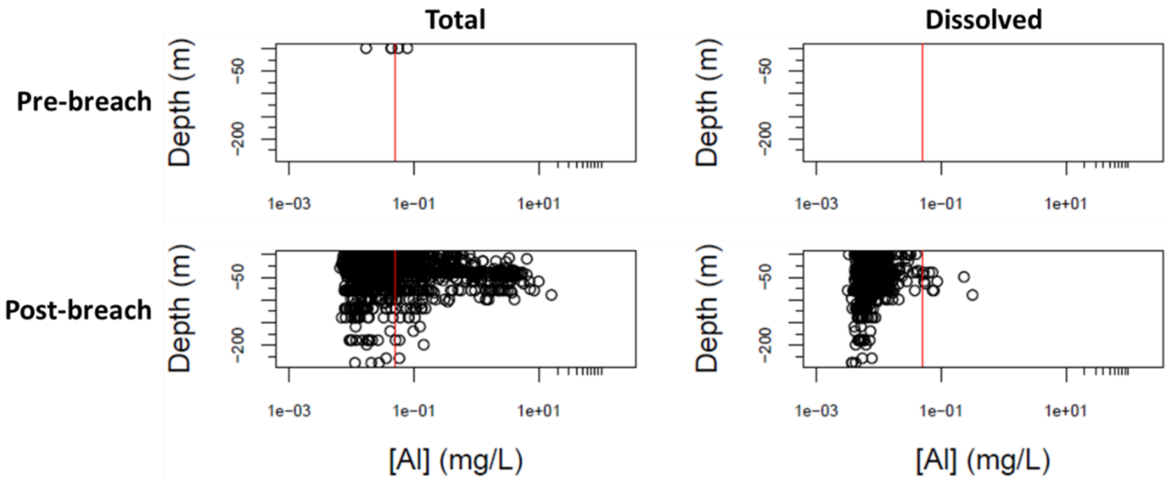

Figure 22. Total and dissolved Al concentrations by depth in the West Arm of Quesnel Lake pre-breach and post-breach. The red vertical line denotes the breach on 4 August 2014.

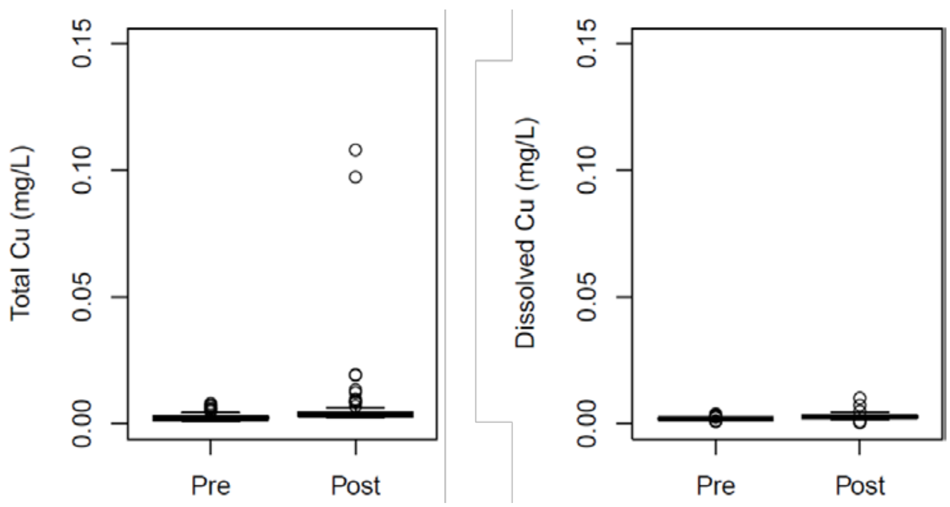

Figure 23. Total and dissolved Cu concentrations (mg/L) in Polley Lake pre- and post-breach.

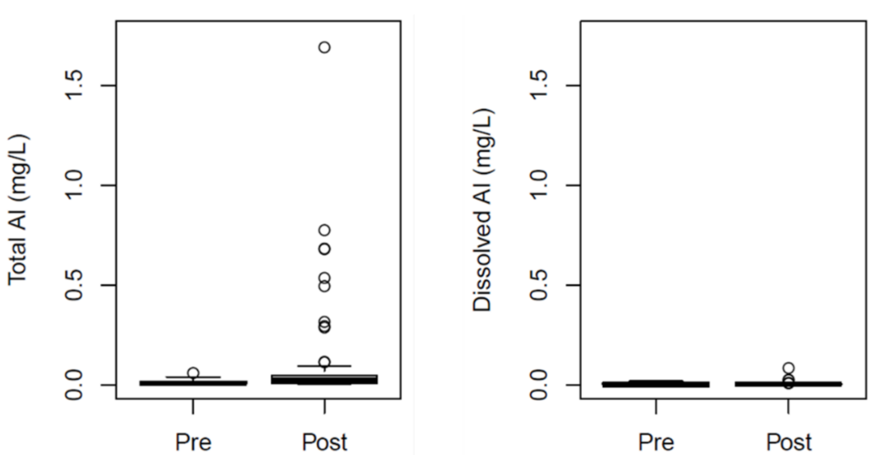

Figure 24. Total and dissolved Al concentrations (mg/L) in Polley Lake pre- and post-breach.

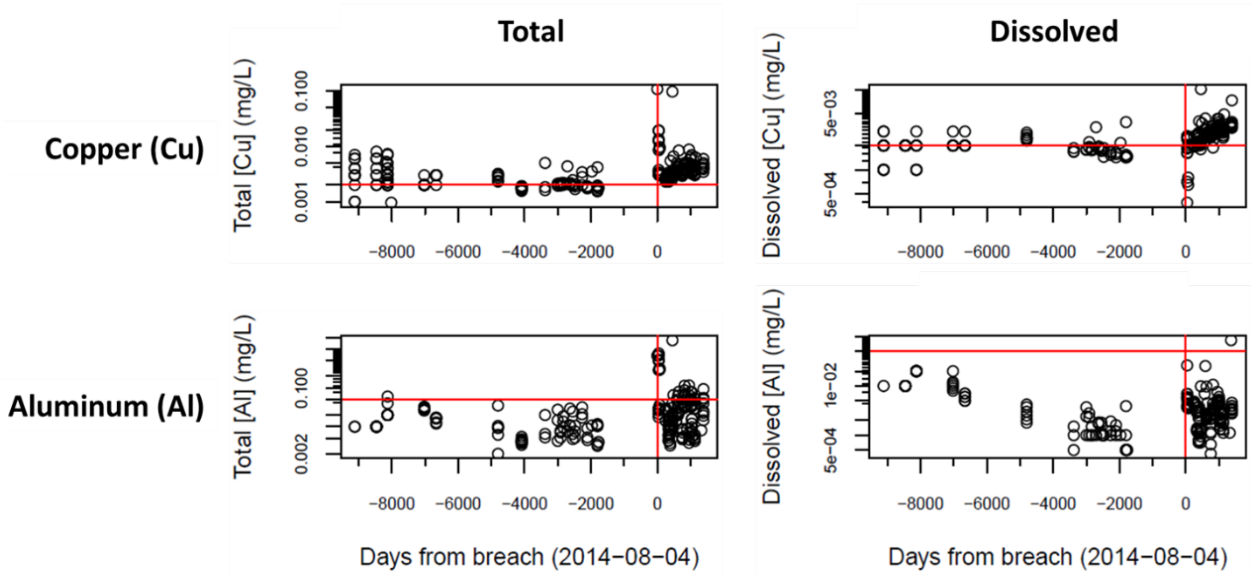

Figure 25. Total and dissolved Cu and Al concentrations in Polley Lake pre-breach (<0 days) and post-breach (≥0 days). The red vertical line denotes the breach on 4 August 2014. For Cu, the red horizontal line denotes the BCENV WQG for total Cu (water hardness of 57 mg/L as $CaCO_3$). There currently is not a BCENV WQG for dissolved Cu [13]. For Al, the red horizontal line marks the BCENV WQG for dissolved Al (pH ≥ 6.5), as there is currently no WQG for total Cu [13].

4.3. Sediment

Sediment sampling efforts were minimal pre- and post-breach (Table 6; Fig. 4 and 5). Metal concentrations were measured in only a small number of sediment samples included in the database (Table 6). Only the West Arm of Quesnel Lake has enough data for a pre- and post-breach comparison since, for example, only 1 of 26 samples was from the North Arm (Table 6). Concentrations of Se differed pre- and post-breach (Wilcoxon rank sum test: $W = 19$, $p = 0.03$), but not Al ($W = 49$, $p = 0.50$), As ($W = 45$, $p = 0.71$), Cu ($W = 59$, $p = 0.13$), or V ($W = 49$, $p = 0.48$). Temporal depiction of the data illustrates that pre- and post-breach total As and Cu concentrations exceed the SQG (As: 5.9 [lower] and 17 [upper] mg/kg; Cu: 35.7 [lower] and 197 [upper] mg/kg; Fig. 26) [16]. Selenium concentrations exceed the SQG (2 mg/kg) pre-breach and fell at or below SQG post-breach (Fig. 26) [13]. There currently are no SQG for Al or V for comparison.

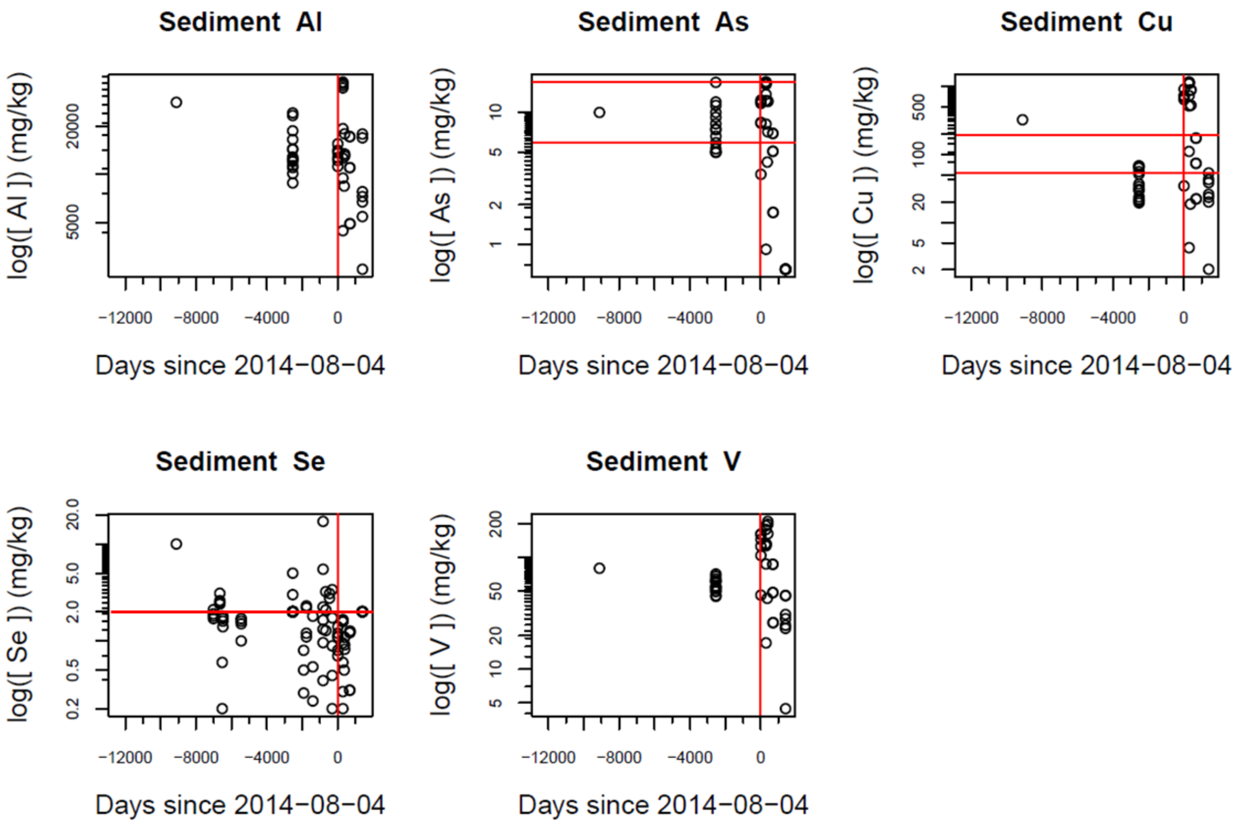

Figure 26. Sediment Al, As, Cu, Se, and V concentrations (mg/L) in the West Arm of Quesnel Lake pre-breach (<0 days) and post-breach (≥0 days). The vertical line denotes the breach on 4 August 2014. The horizontal lines mark the SQG for Se (2.0 mg/kg) and the upper and lower SQGs for As (5.9 [lower] and 17 [upper] mg/kg) and Cu (35.7 [lower] and 197 [upper] mg/kg) [13,16]. There are no SQG for Al or V.

4.4. Fish

Fish were the most sampled biota for the database. Thirteen species of fish are represented in the database (Table 7). The majority of fish data is on size, sex, age, and spawning condition, while there are few data on the concentration of metals in fish. Eight of the 13 species of fish—Burbot (*Lota lota*), Lake Trout (*Salvelinus namaycush*), Largescale Sucker (*Catostomus macrocheilus*), Mountain Whitefish (*Prosopium williamsoni*), Peamouth Chub (*Mylocheilus caurinus*), Rainbow Trout (*Oncorhynchus mykiss*), Sockeye Salmon (*Oncorhynchus nerka*), and White Sucker (*Catostomus commersonii*)—were sampled for metals. Concentrations of metals were measured in either whole bodies of fish or dissected physiologically sensitive tissues (gills, liver, and gonads, muscle) and the remaining carcass separately. We focused metal concentrations in physiological sensitive tissues that are more informative to the condition of an organism than those in the whole body (Table 8). Furthermore, whole bodies were only sampled from Fraser River and Quesnel Lake, while tissues were sampled from these waterbodies and six additional waterbodies. However, there has not been an adequate sampling effort to be able to statistically compare tissue metal and major ion concentrations pre- and post-breach (Table 8). Instead, we compared post-breach metal (Al, As, Cu, and Se) and major ion (Ca and Na) concentrations in tissues (carcass, gills, gonad, liver, and muscle) of Rainbow Trout and Sockeye Salmon from Quesnel Lake (Fig. 27–38) and Polley Lake (Fig. 39). Major ions were included because metals are known to impair ionoregulation in fish [19,20].

4.4.1. Quesnel Lake

In Quesnel Lake, Cu and Se concentrations were highest in the liver of both Rainbow Trout (Cu, $F_{(4,38)} = 25.25$, $p < 0.001$, Fig. 29; Se, $F_{(4,38)} = 24.47$, $p < 0.001$, Fig. 30) and Sockeye Salmon (Cu, $F_{(4,76)} = 136.2$, $p < 0.001$, Fig. 35; Se, $F_{(4,76)} = 23.66$, $p < 0.001$, Fig. 36). However, Cu and Se concentrations were much higher in Sockeye Salmon liver (Cu, min. > 100 and max. > 600; Se, min. < 10 and max. > 60) than in Rainbow Trout liver (Cu, min. > 10 and max. < 100; Se, min. > 3 and max. < 14). Selenium concentrations in the muscle of Rainbow Trout and Sockeye Salmon did not exceeded the BCENV guidelines for muscle tissue (4 mg/kg), however, Se concentrations in Rainbow Trout muscle was near the guideline (approximately 0.5–3.5 mg/kg dw) [13].

Aluminum concentrations were highest in Rainbow Trout carcass ($F_{(4,38)} = 47.71$, $p < 0.001$; Fig. 27) and Sockeye Salmon gills ($F_{(4,76)} = 31.38$, $p < 0.001$; Fig. 33). The concentration of As was also highest in Sockeye Salmon liver ($F_{(4,76)} = 13.97$, $p < 0.001$; Fig. 34), while As concentrations in Rainbow Trout were higher in the liver than gonad ($p = 0.005$) and muscle ($p < 0.001$) but not gills ($p = 0.07$) and carcass ($p = 0.10$; Fig. 28). Calcium concentrations were highest in the carcass and gills of Rainbow Trout ($F_{(4,38)} = 19.49$, $p < 0.001$; Fig. 31) and gills in Sockeye Salmon ($F_{(4,76)} = 294.8$, $p < 0.001$; Fig. 37). In Rainbow trout Na concentrations are higher in carcass and gills than liver ($p = 0.01$ and 0.04, respectively) and muscle ($p = 0.01$ and 0.02, respectively; Fig. 32). There is a marginal statistical significance between carcass and gonad ($p = 0.05$). Sodium concentrations were highest in gonad and muscle of Sockeye Salmon ($F_{(4,76)} = 20.11$, $p < 0.001$; Fig. 38).

4.4.2. Polley Lake

Only Se in Rainbow Trout liver and muscle was adequately measured post-breach for analysis. The concentration of Se was higher in liver than muscle tissue ($F_{(1,16)} = 11.90$, $p = 0.003$, Fig. 39). The liver concentrations are consistent with those in Quesnel Lake with the exception of a single fish liver with > 25 mg/kg Se.

Table 6. Sediment sampling effort pre-breach and post-breach. The bolded waterbodies are those with adequate sampling pre- and post-breach to analyze for metals. Only Quesnel Lake (bolded) was sufficiently sampled for a pre- to post-breach comparison of metals. *denotes waterbodies not affected by the breach.

Waterbody	**Total Samples**	**Pre-breach**	**Post-breach**
Blackwater River*	1	1	0
Bootjack Creek*	11	11	0
Bootjack Lake*	10	9	1
Cariboo River*	2	2	0
Cottonwood River*	1	1	0
Edney Creek	12	12	0
Frypan Lake*	2	2	0
Gavin Lake*	2	0	2
Hazeltine Creek	58	57	1
Horsefly River*	5	5	0
Jacobie Creek*	1	1	0
Little Lake*	1	0	1
Main embankment seepage pond	2	2	0
Morehead Creek*	1	1	0
MPMC	7	0	7
Nazko River*	1	1	0
North Dump Creek	2	2	0
Polley Flats	2	0	2
Polley Lake	13	12	1
Quesnel Lake	26	7	19
Quesnel River*	9	9	0
Trio Creek*	1	1	0
Trio Lake*	2	2	0
West Duck Pond*	2	0	2

Table 7. Fish species represented in the database by waterbody.

Waterbody	Genus	Species	Count
Bootjack Creek	*Oncorhynchus*	*mykiss*	79
Bootjack Lake	*Catostomus*	unknown	36
	Catostomus	*catostomus*	27
	Oncorhynchus	*mykiss*	99
Edney Creek	*Catostomus*	*catostomus*	1
	Oncorhynchus	*mykiss*	475
	Rhinichthys	*cataractae*	3
Fraser River	*Oncorhynchus*	*mykiss*	22
Frypan Lake	*Oncorhynchus*	*mykiss*	15
Hazeltine Creek	*Catostomus*	unknown	1
	Catostomus	*columbianus*	2
	Catostomus	*macrocheilus*	8
	Lota	*lota*	82
	Mylocheilus	*caurinus*	17
	Oncorhynchus	*kisutch*	1
	Oncorhynchus	*mykiss*	914
	Prosopium	*williamsoni*	2
	Rhinichthys	*cataractae*	16
	Richardsonius	*balteatus*	6
Horsefly River	*Oncorhynchus*	*mykiss*	51
	Oncorhynchus	*tshawytscha*	60
Little Horsefly River	*Oncorhynchus*	*nerka*	39
McKinley Creek	*Oncorhynchus*	*tshawytscha*	1
Morehead Creek	*Oncorhynchus*	*mykiss*	51
Polley Lake	*Catostomus*	*catostomus*	223
	Oncorhynchus	*mykiss*	321
	Richardsonius	*balteatus*	1
Quesnel Lake	*Catostomus*	unknown	7
	Catostomus	*catostomus*	22
	Catostomus	*macrocheilus*	24
	Lota	*lota*	33
	Mylocheilus	*caurinus*	3
	Oncorhynchus	*mykiss*	74
	Oncorhynchus	*nerka*	115
	Prosopium	*williamsoni*	11
	Ptychocheilus	*oregonensis*	65
	Salvelinus	*namaycush*	99
Quesnel River	*Oncorhynchus*	*nerka*	24
	Oncorhynchus	*tshawytscha*	296
Trio Lake	*Oncorhynchus*	*mykiss*	15
Unknown waterbody	*Oncorhynchus*	*mykiss*	5
Whiffle Creek	*Lota*	*lota*	30

Table 8. The number of fish tissue samples that were analyzed for metals and/or major ions pre- and post-breach arranged by lake, species, tissue, and time (pre/post breach). This table does not include which specific metals or ions for which the tissue samples were analyzed.

Waterbody	Genus	Species	Tissue	Time	Count
Bootjack Lake	*Catostomus*	*catostomus*	gonad	Pre	5
	Catostomus	*catostomus*	liver	Post	8
	Catostomus	*catostomus*	muscle	Post	8
	Catostomus	*catostomus*	muscle	Pre	5
	Oncorhynchus	*mykiss*	gonad	Pre	5
	Oncorhynchus	*mykiss*	liver	Post	4
	Oncorhynchus	*mykiss*	liver	Pre	10
	Oncorhynchus	*mykiss*	muscle	Post	4
	Oncorhynchus	*mykiss*	muscle	Pre	10
Fraser River	unknown	unknown	unknown	Post	13
	Oncorhynchus	*mykiss*	unknown	Post	9
	Oncorhynchus	*mykiss*	gonad	Post	4
	Oncorhynchus	*mykiss*	liver	Post	4
	Oncorhynchus	*mykiss*	muscle+skin	Post	5
Frypan Lake	*Oncorhynchus*	*mykiss*	gonad	Pre	5
	Oncorhynchus	*mykiss*	muscle	Pre	10
Hazeltine Creek	*Oncorhynchus*	*mykiss*	gonad	Pre	26
	Oncorhynchus	*mykiss*	muscle	Pre	26
Polley Lake	*Catostomus*	*catostomus*	gonad	Pre	15
	Catostomus	*catostomus*	liver	Post	9
	Catostomus	*catostomus*	muscle	Post	9
	Catostomus	*catostomus*	muscle	Pre	15
	Oncorhynchus	*mykiss*	gonad	Pre	15
	Oncorhynchus	*mykiss*	liver	Post	9
	Oncorhynchus	*mykiss*	liver	Pre	10
	Oncorhynchus	*mykiss*	muscle	Post	9
	Oncorhynchus	*mykiss*	muscle	Pre	20
Quesnel Lake	*Catostomus*	*catostomus*	liver	Post	1
	Catostomus	*catostomus*	muscle	Post	1
	Catostomus	*catostomus*	muscle	Pre	10
	Catostomus	*macrocheilus*	gonad	Pre	7
	Catostomus	*macrocheilus*	muscle	Pre	7
	Lota	*lota*	gonad	Post	7
	Lota	*lota*	liver	Post	11
	Lota	*lota*	muscle	Post	11
	Mylocheilus	*caurinus*	unknown	Post	3
	Oncorhynchus	*mykiss*	carcass	Post	12
	Oncorhynchus	*mykiss*	gills	Post	12
	Oncorhynchus	*mykiss*	gonad	Post	2
	Oncorhynchus	*mykiss*	gonad	Pre	10

Waterbody	**Genus**	**Species**	**Tissue**	**Time**	**Count**
	Oncorhynchus	*mykiss*	liver	Post	14
	Oncorhynchus	*mykiss*	muscle	Post	3
	Oncorhynchus	*mykiss*	muscle	Pre	23
	Oncorhynchus	*nerka*	unknown	Post	36
	Oncorhynchus	*nerka*	carcass	Post	17
	Oncorhynchus	*nerka*	gills	Post	17
	Oncorhynchus	*nerka*	gonad	Post	10
	Oncorhynchus	*nerka*	liver	Post	27
	Oncorhynchus	*nerka*	muscle	Post	10
	Prosopium	*williamsoni*	gonad	Post	3
	Prosopium	*williamsoni*	liver	Post	4
	Prosopium	*williamsoni*	muscle	Post	4
	Ptychocheilus	*oregonensis*	unknown	Post	63
	Ptychocheilus	*oregonensis*	gonad	Post	1
	Ptychocheilus	*oregonensis*	liver	Post	1
	Ptychocheilus	*oregonensis*	muscle	Post	1
	Salvelinus	*namaycush*	gonad	Post	34
	Salvelinus	*namaycush*	liver	Post	51
	Salvelinus	*namaycush*	muscle	Post	53
Quesnel River	*Oncorhynchus*	*nerka*	gonad	Post	10
	Oncorhynchus	*nerka*	liver	Post	10
	Oncorhynchus	*nerka*	muscle	Post	10
Trio Lake	*Oncorhynchus*	*mykiss*	gonad	Pre	5
	Oncorhynchus	*mykiss*	muscle	Pre	10
Unknown waterbody	*Oncorhynchus*	*mykiss*	muscle+skin	Pre	5

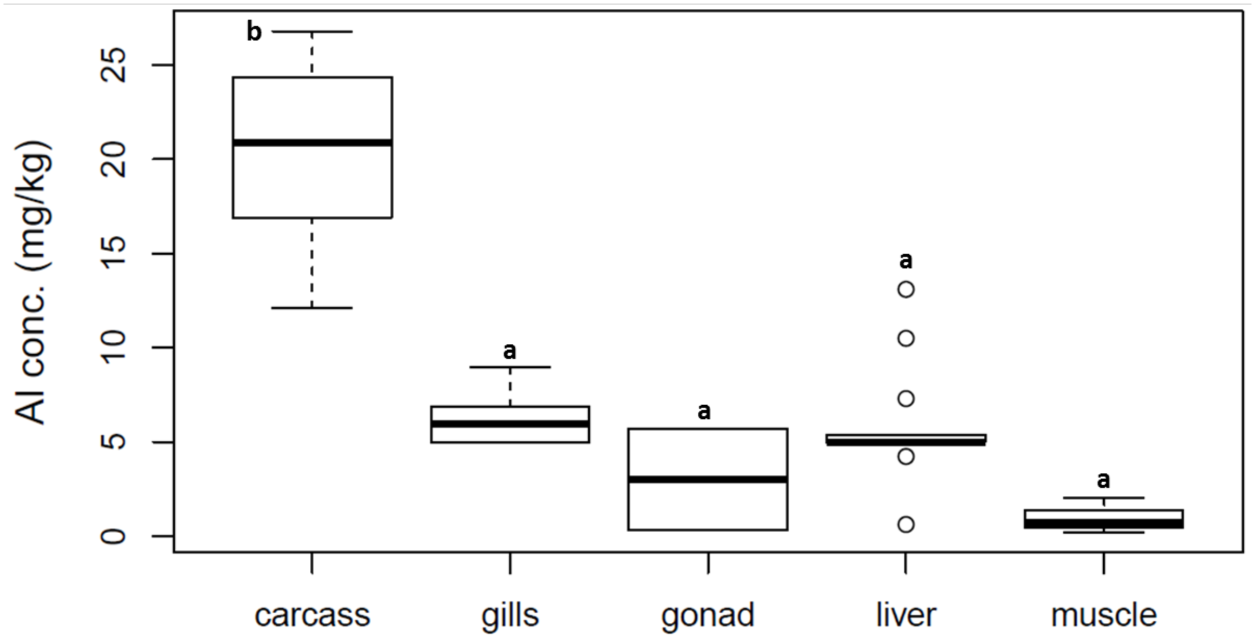

Figure 27. Concentrations of Al in Rainbow Trout carcass, gills, gonad, liver, and muscle (dry weight) from Quesnel Lake post-breach. Letters denote significant differences ($p < 0.05$).

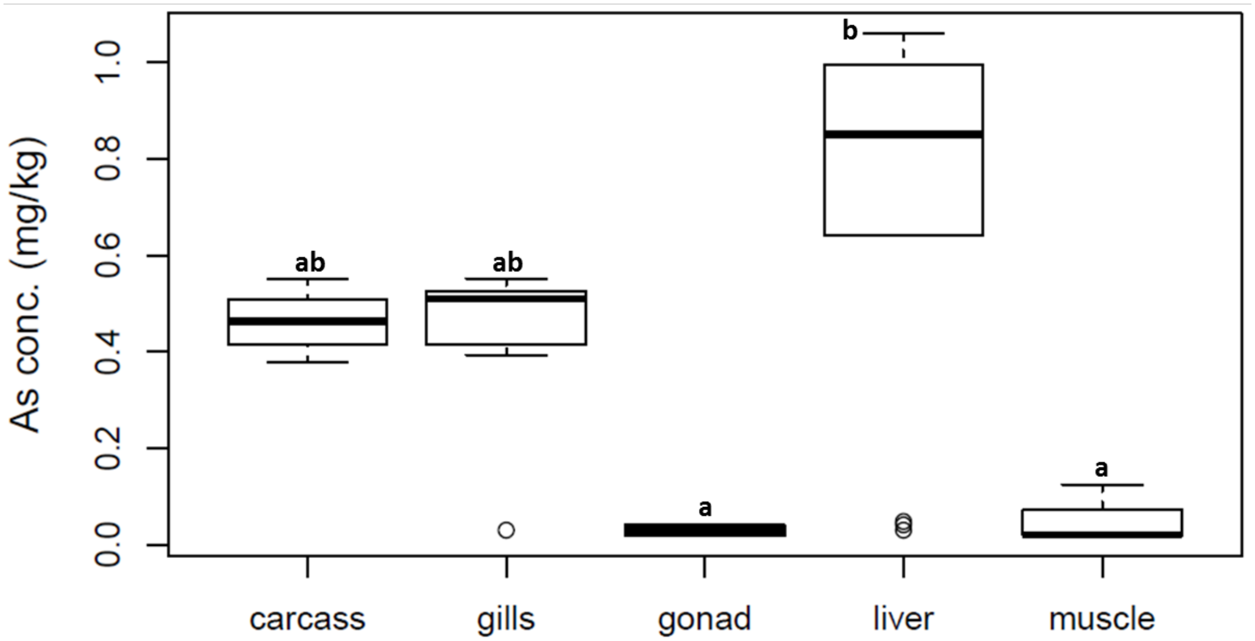

Figure 28. Concentrations of As in Rainbow Trout carcass, gills, gonad, liver, and muscle (dry weight) from Quesnel Lake post-breach. Letters denote significant differences ($p < 0.05$).

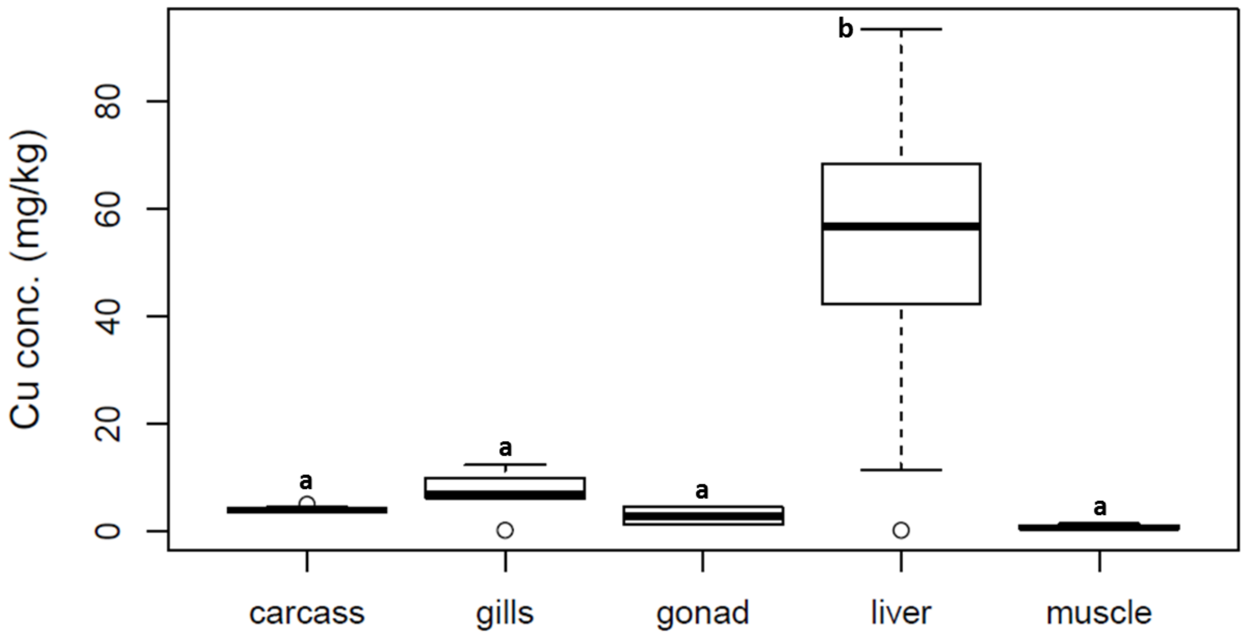

Figure 29. Concentrations of Cu in Rainbow Trout carcass, gills, gonad, liver, and muscle (dry weight) from Quesnel Lake post-breach. Letters denote significant differences ($p < 0.05$).

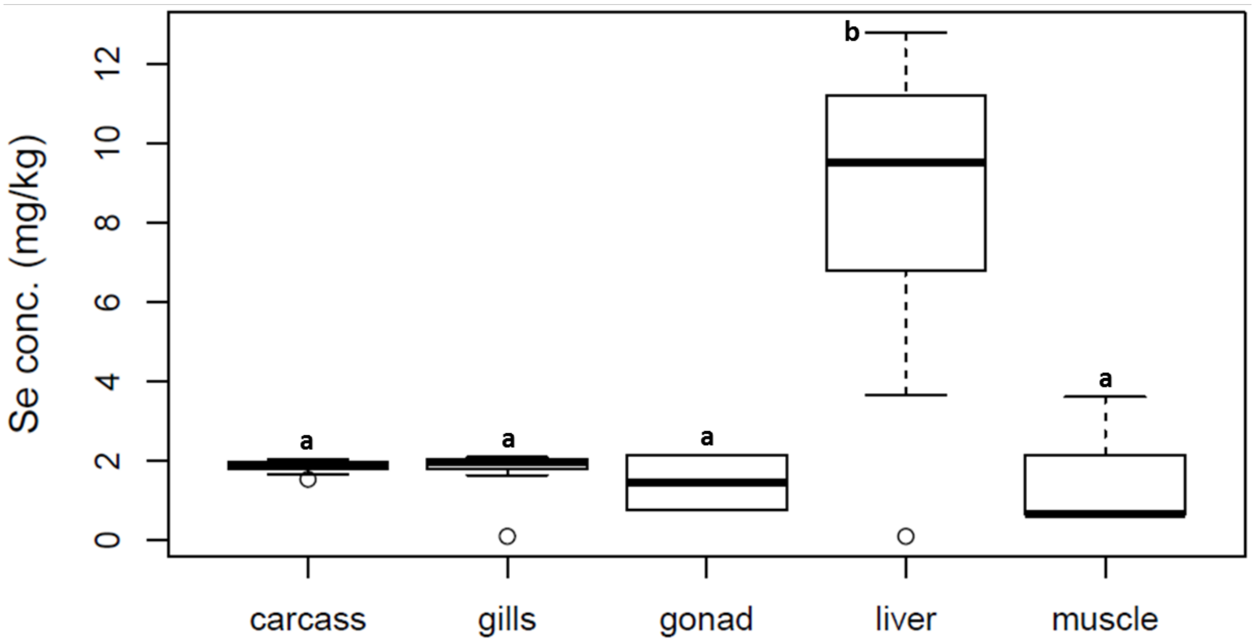

Figure 30. Concentrations of Se in Rainbow Trout carcass, gills, gonad, liver, and muscle (dry weight) from Quesnel Lake post-breach. Letters denote significant differences ($p < 0.05$).

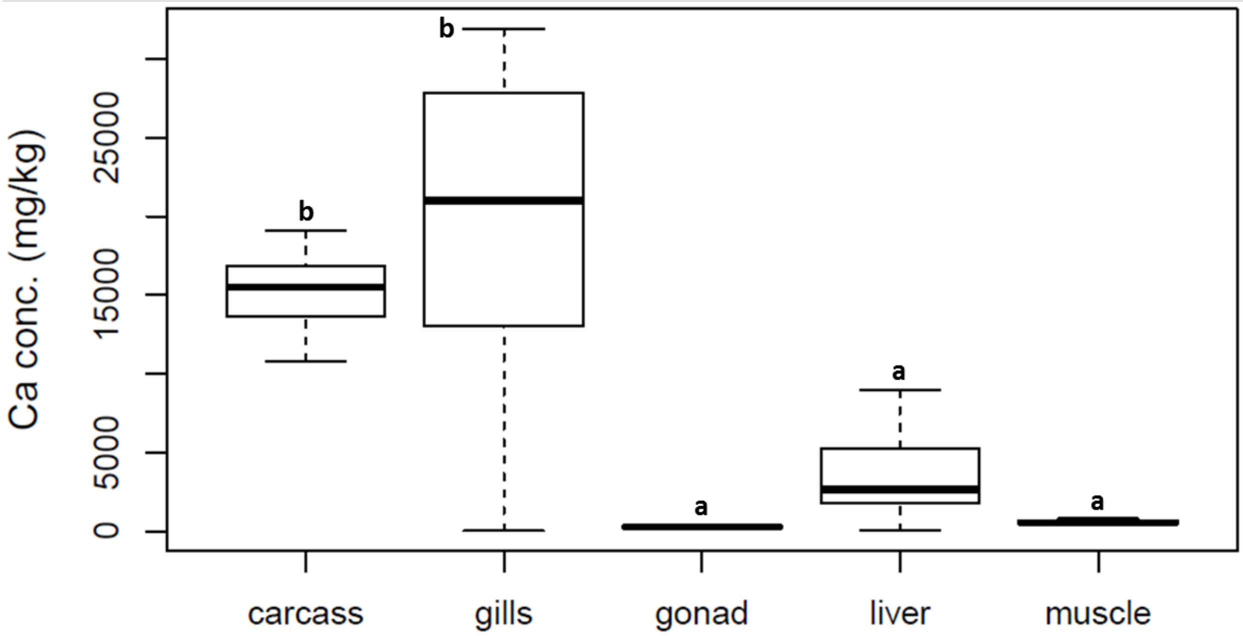

Figure 31. Concentrations of Ca in Rainbow Trout carcass, gills, gonad, liver, and muscle (dry weight) from Quesnel Lake post-breach. Letters denote significant differences ($p < 0.05$).

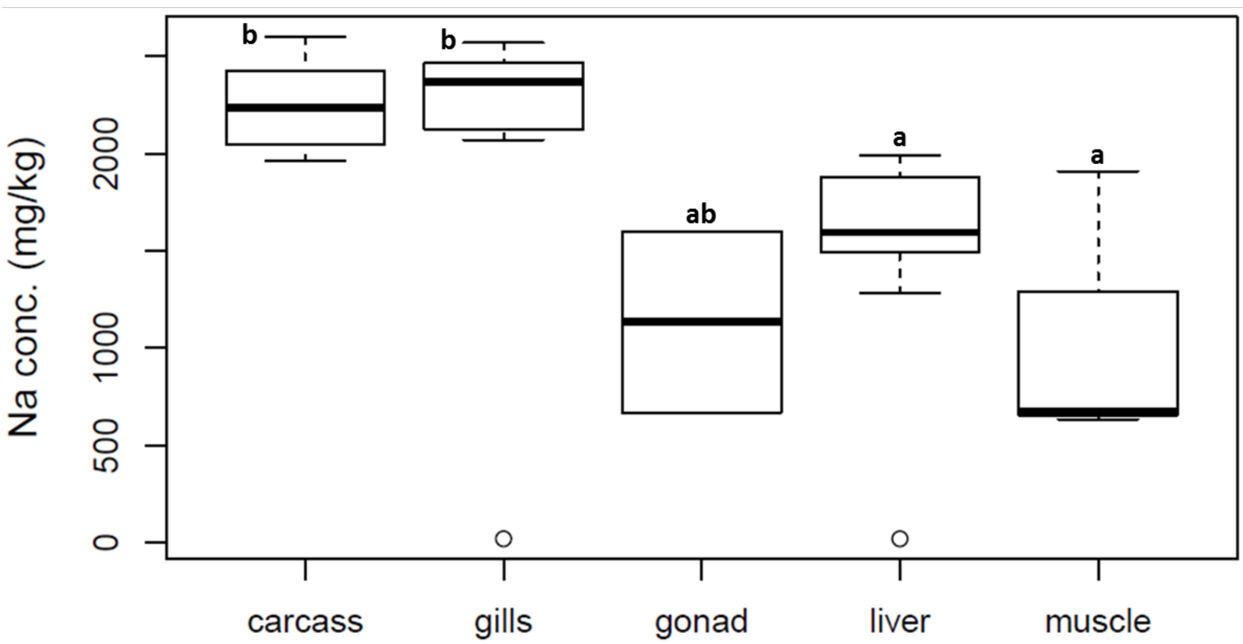

Figure 32. Concentrations of Na in Rainbow Trout carcass, gills, gonad, liver, and muscle (dry weight) from Quesnel Lake post-breach. Letters denote significant differences ($p < 0.05$).

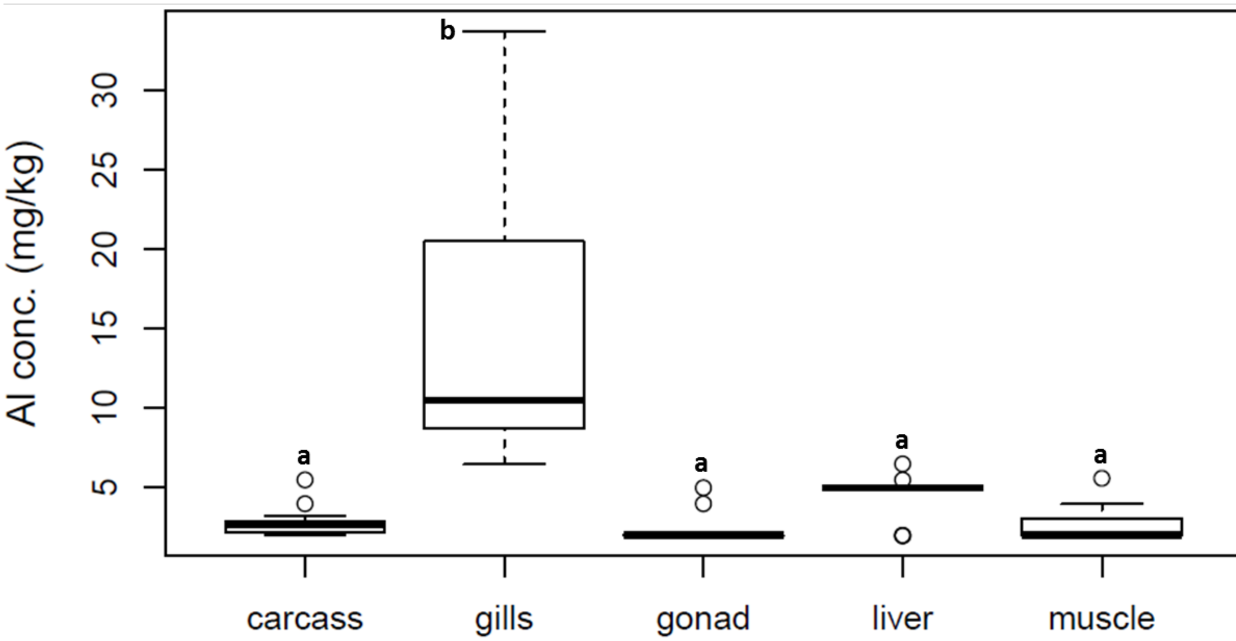

Figure 33. Concentrations of Al in Sockeye Salmon carcass, gills, gonad, liver, and muscle (dry weight) from Quesnel Lake post-breach. Letters denote significant differences ($p < 0.05$).

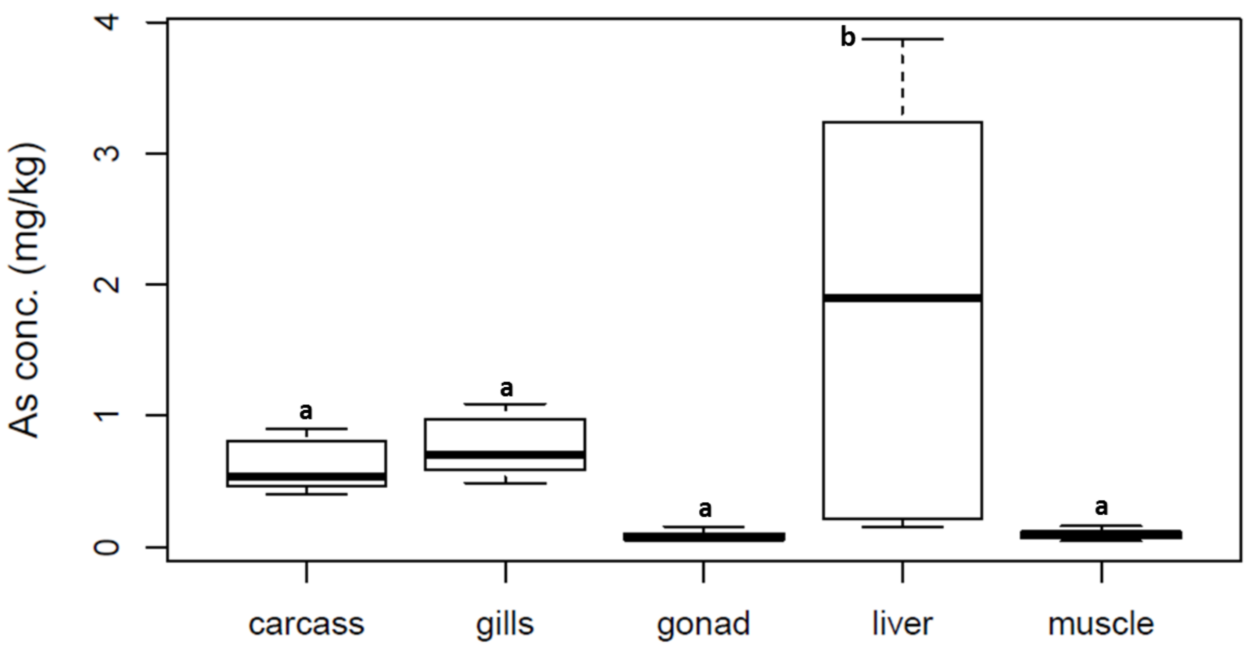

Figure 34. Concentrations of As in Sockeye Salmon carcass, gills, gonad, liver, and muscle (dry weight) from Quesnel Lake post-breach. Letters denote significant differences ($p < 0.05$).

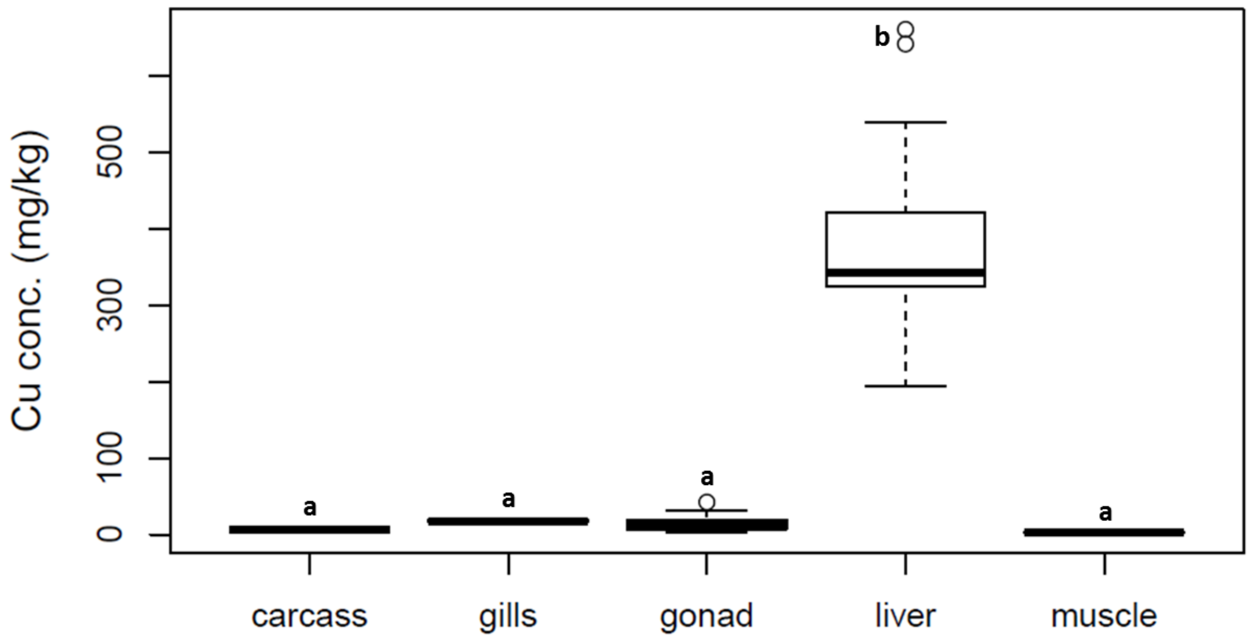

Figure 35. Concentrations of Cu in Sockeye Salmon carcass, gills, gonad, liver, and muscle (dry weight) from Quesnel Lake post-breach. Letters denote significant differences ($p < 0.05$).

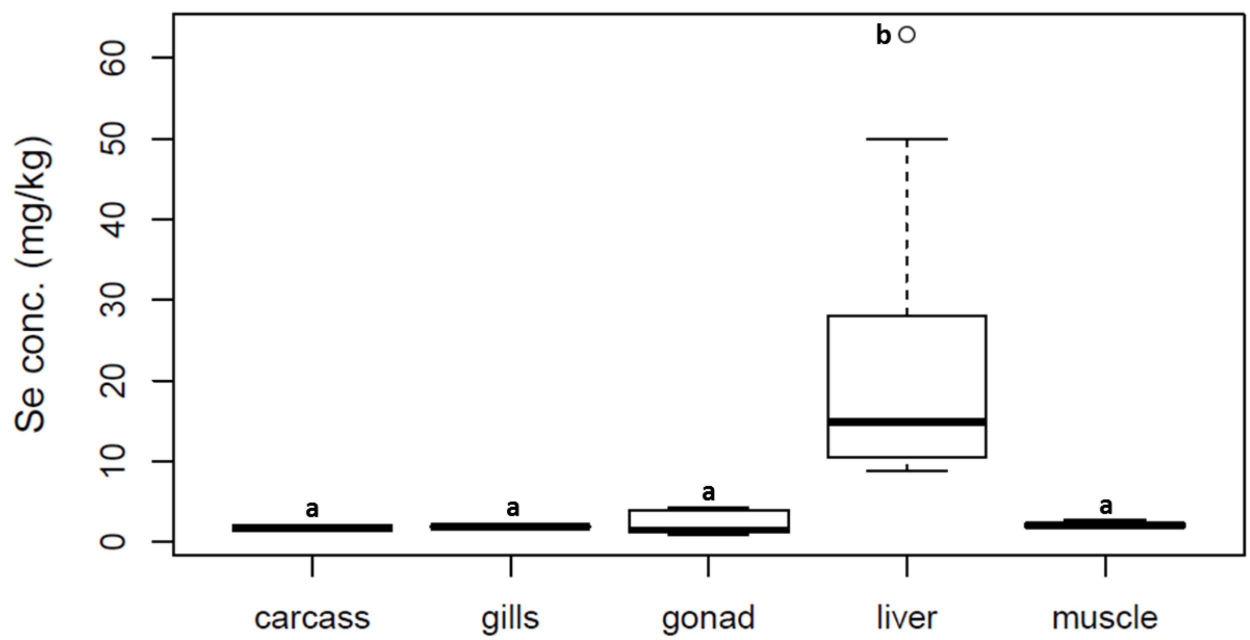

Figure 36. Concentrations of Se in Sockeye Salmon carcass, gills, gonad, liver, and muscle (dry weight) from Quesnel Lake post-breach. Letters denote significant differences ($p < 0.05$).

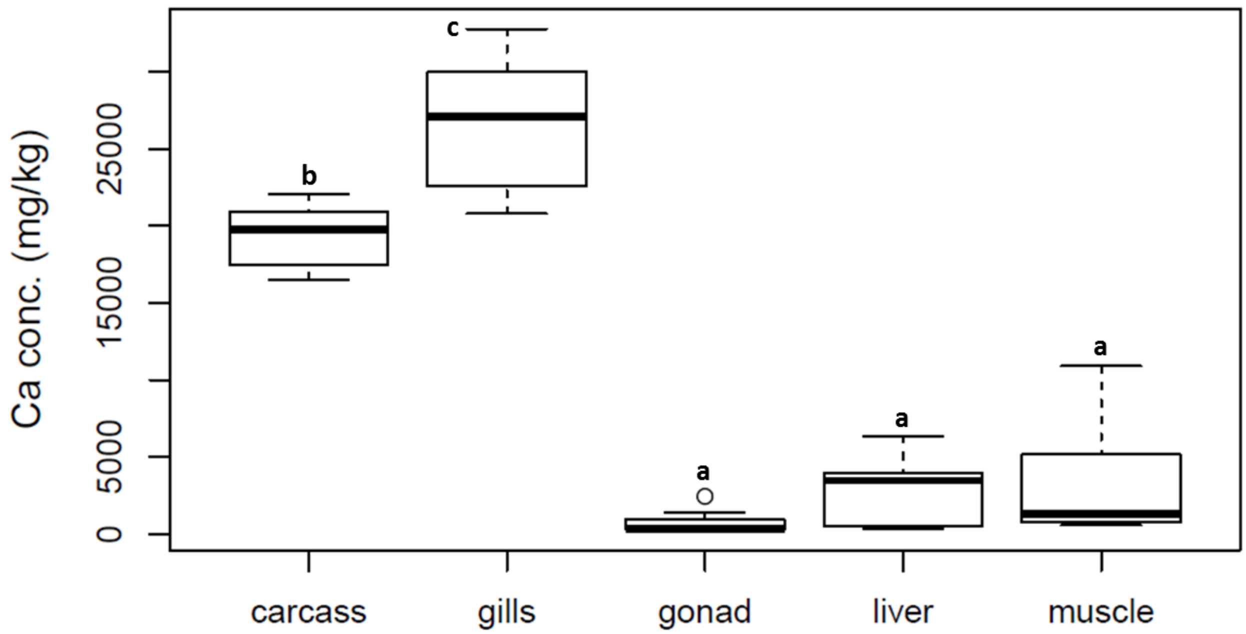

Figure 37. Concentrations of Ca in Sockeye Salmon carcass, gills, gonad, liver, and muscle (dry weight) from Quesnel Lake post-breach. Letters denote significant differences ($p < 0.05$).

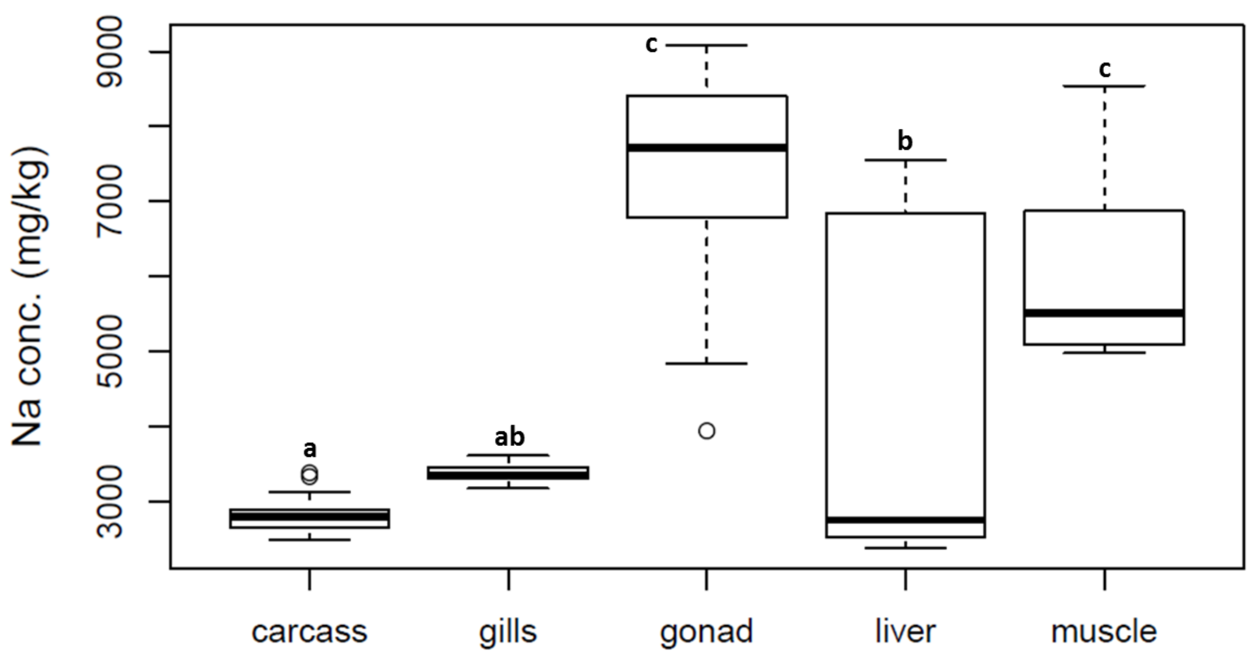

Figure 38. Concentrations of Na in Sockeye Salmon carcass, gills, gonad, liver, and muscle (dry weight) from Quesnel Lake post-breach. Letters denote significant differences ($p < 0.05$).

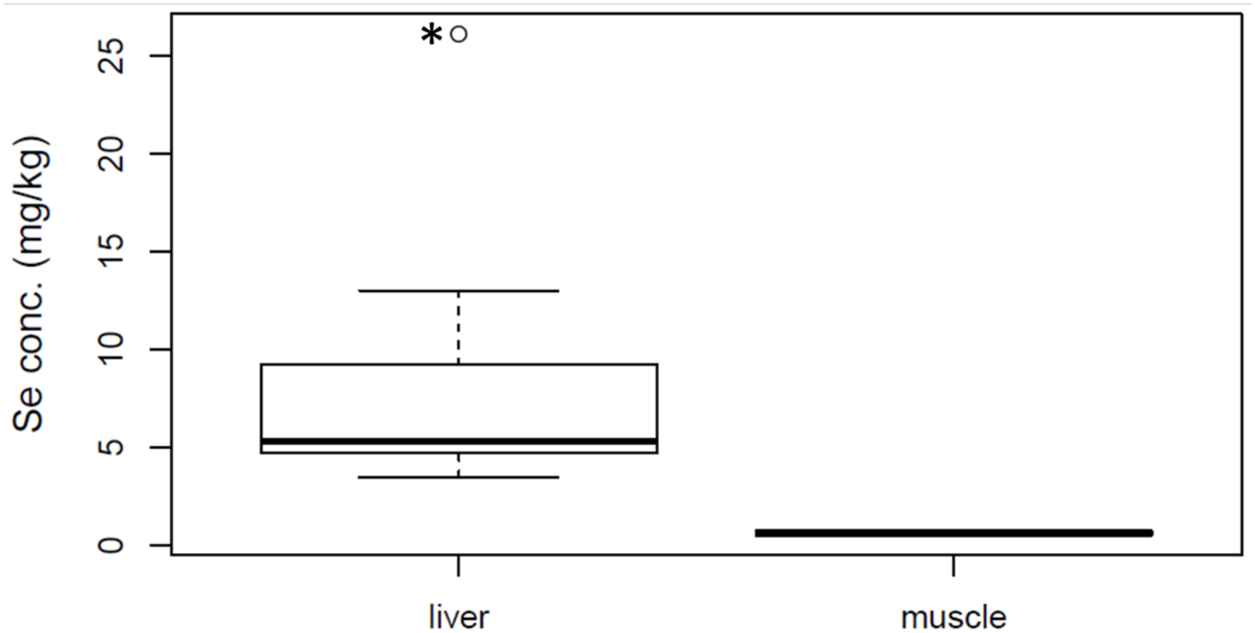

Figure 39. Concentrations of Se in Rainbow Trout carcass, gills, gonad, liver, and muscle (dry weight) from Polley Lake post-breach. Asterisk denotes significant differences ($p < 0.05$).

4.5. Benthic invertebrates

The disparity in the pre- and post-breach datasets requires many assumptions to be made for this analysis. Most of the pre-breach data were collected in 2007; whereas, almost all of the post-breach data were from October 2014 (a couple of months after the breach). Not all waterbodies had both pre- and post-breach data. The post-breach community of Quesnel Lake was dominated by Chaoboridae and Chironomidae, while Trombidiformes dominated the Polley Lake community. Polley Lake had the lowest diversity of all waterbodies sampled pre- and post-breach, which did not change (Shannon's diversity index < 0.01; Table 9). Quesnel Lake's diversity index dropped from 2.83 pre-breach to 0.69 post-breach (Table 9). Our analysis suggests that the breach affected the communities of Quesnel Lake causing a decrease in species diversity.

Table 9. Shannon's diversity index of benthic invertebrate families by waterbody pre- and post-breach.

Waterbody	Pre-breach	Post-breach

Baker Creek		3.18
Cariboo River		3.43
Edney Creek	3.58	
Hazeltine Creek	3.61	
Mons Creek		3.18
Polley Lake	<0.01	<0.01
Quesnel Lake	2.83	0.69
Quesnel River		3.43
Twinflower Creek		3.30
Whiffle Creek	3.43	

4.6. Plankton

Only Polley Lake is represented by pre-breach data, while Polley Lake, Quesnel Lake, and Quesnel River are represented by post-breach data (Table 10). Consequently, only the plankton community of Polley Lake could be compared pre-and post-breach. The diversity of Polley Lake was 2.04 pre-breach and 1.4 post-breach suggesting that there was a loss of diversity. The species richness of Polley Lake was 42 pre-breach and 66 post-breach (Table 10). There are 41 families in common between pre- and post-breach datasets, representing 97.6% of the original composition. However, it is impossible to know whether individual species are affected by only assessing diversity.

Table 10. Shannon's diversity index and species richness of plankton families by waterbody pre- and post-breach.

	Shannon's diversity index		**Species richness**	
Waterbody	**Pre-breach**	**Post-breach**	**Pre-breach**	**Post-breach**
Polley Lake	2.04	1.41	42	66
Quesnel Lake		1.73		74
Quesnel River		2.25		30

5. Discussion

5.1. Are the concentrations of metals and phosphorus higher in Quesnel Lake and other affected waterbodies (e.g., Polley Lake and Hazeltine Creek) post-breach than pre-breach and in regional reference waterbodies? How do these values compare to the BCENV WQG and SQG for the protection of freshwater aquatic life?

5.1.1. Water metals

Concentrations of metals in water from the database exceeded BCENV's guidelines for the protection of freshwater aquatic life. Water Cu and Al concentrations exceeded the WQGs post-breach, while only Al surpassed the WQG pre-breach. Water As concentrations did not surpass the WQG. Other metals were not examined because of small sample sizes and huge left-censorship (>50%; Table 3).

Water Cu (total) concentrations in Quesnel Lake, Polley Lake, Hazeltine Creek, and Edney Creek did not exceed the WQG (0.007 mg/L at 57 mg/L as $CaCO_3$) prior to the breach (Table 4). Following the breach, the mean Cu concentration in Quesnel Lake and Hazeltine Creek were 1.4 and 2.9 times the WQG, respectively (Table 5). Although Cu concentrations in Polley Lake and Edney Creek did not exceed the WQG pre- or post-breach, the Cu concentrations were higher post-breach than pre-breach (Table 4 and 5). Water Cu concentrations post-breach in Quesnel Lake and Hazeltine Creek are 1.3 and 2.5 times the concentration (0.008 mg/L at water hardness of 90 mg/L as $CaCO_3$) known to depress the olfactory response in Rainbow Trout within two hours of exposure [21]. As water hardness diminishes Cu toxicity, the concentration required to depress olfactory responses is likely lower than 0.008 mg/L, as Quesnel Lake and other waterbodies of interest have lower water hardness [22]. The 7-d LC50 values for *H. azteca* are 0.036 mg/L in soft water (18 mg/L as $CaCO_3$) and 0.12 mg/L in hard water (124 mg/L as $CaCO_3$)[23]. The 7-d LC50 for *H. azteca* in Quesnel Lake and other waterbodies of interest would likely fall between these values based only on water hardness. Current Cu concentrations have dropped and are generally meeting the WQGs in all waterbodies.

Water Al (dissolved) concentrations were at the WQG only in Hazeltine Creek pre-breach (Table 4). Following the breach, Al concentrations in Edney Creek exceeded the WQG by 1.2 times and increased in Polley Lake, while concentrations declined in Hazeltine Creek and Quesnel Lake (Table 5). Post-breach concentrations did not surpass chronic LC50 values at similar pH for *C. dubia* (1.91 mg/L at pH 7.15), *D. magna* (0.74 mg/L at pH 8.30), or *P. promelas* (3.29 mg/L at pH 7.24–8.15) [24,25]. Current Al concentrations have dropped and are generally meeting the WQGs in all waterbodies.

Water As (total) concentrations did not exceed the WQG in any of the four waterbodies examined (Table 4 and 5). Following the breach, As concentrations remained constant and highest in Edney Creek, increased in Polley Lake and Hazeltine Creek, and decreased in Quesnel Lake. Concentrations of As in these waterbodies are below those concentrations shown to induce toxicity after chronic exposures [23,26]. The 7-d LC50 values for *H. azteca* are 0.49 mg/L in soft water (18 mg/L as $CaCO_3$) and 0.43 mg/L in hard water (124 mg/L as $CaCO_3$) [23]. After a 29-d exposure, Fathead Minnows exhibited reduced weight and length at ≥ 4.3 mg/L As and reduced survival from hatch to the test termination at 16.5 mg/L As compared to controls [26]. Current As concentrations have dropped and are generally meeting the WQGs in all waterbodies.

5.1.2. Water phosphorus

Based on our pre- and post-breach analysis, the breach likely contributed to an increase in total P in Quesnel Lake, Polley Lake, and Hazeltine Creek as concentrations of P differed pre- and post-breach in these waterbodies (Fig. 6–87 and 11–13). Total P levels in Quesnel Lake have returned to background levels after the breach but concentrations in Polley Lake and Hazeltine Creek remain elevated. Locals at the 2018 QRRC Open House reported higher than average algal growth in Quesnel Lake. Algal blooms can occur at high- and low-nutrient conditions in lakes [27]. Thus, it is possible that the P input from the breach affected algal growth in Quesnel Lake. However, additional research on the bloom-forming cyanobacteria and the P and N cycling of Quesnel Lake is necessary to determine whether the breach had an effect on algal growth in the lake.

5.1.3. Sediment

Sediment Cu, As, and Se concentrations exceeded SQGs, while there are no SQGs for Al and V. Sediment Cu and As concentrations in the West Arm of Quesnel Lake exceeded the lower and upper SQG, and Se concentrations exceeded the SQG both pre- and post-breach (Fig. 30). Only the concentration of Se was statistically higher after the breach than before. However, small samples size and sporadic sampling made it difficult to determine whether the breach had an impact on the concentrations of other metals in sediment. Some Cu concentrations in Quesnel Lake exceed the 14-d LC50 values for *C. dubia* (32 mg/kg), *D. magna* (37.4 mg/kg), *H. azteca* (247 mg/kg), and *P. promelas* (286 mg/kg) [28]. The As concentrations do not exceed the 10-d LC50 values for *H. azteca* (532 mg/kg dw) [29]. Sediment Se concentrations are up to 10 times the sediment-based WQG, and up to 5 times the concentration observed to cause toxicity in fish and wildlife in mountain streams (4.0 mg/kg) [30].

5.2. Are Cu and other metals associated with the tailing that were deposited into Quesnel Lake and other waterbodies (e.g., Polley Lake and Hazeltine Creek) by the breach available to biota (i.e. fish, benthic invertebrates, plankton, and amphibians)?

Fish are the only biota adequately sampled to examine accumulation of metals surrounding the tailings impoundment breach. Based on the presence of essential (e.g., Cu and Se) and non-essential elements (e.g., Al and As) in fish tissue confirms that these elements are indeed bioavailable to fish [19,20]. However, we cannot attribute the presence or tissue concentrations specifically to the breach because pre-breach and regional reference data are missing in the dataset. In other words, we cannot show cause and effect within Quesnel Lake despite evidence that these elements are bioavailable to fish.

Current concentrations of Cu in the livers of Rainbow Trout and Sockeye Salmon from Quesnel Lake are as high as 2 times and approximately 4–15 times, respectively, the conservative Cu liver concentration threshold of Yellow Perch (*Perca* flavescens; 50 mg/kg) [31–33]. The Cu liver concentration threshold is the concentration of Cu in the liver that when exceeded represents a risk of toxicity [31]. However, at this time there are no tissue accumulation threshold concentrations established for any salmonid species. As many salmonids including Rainbow Trout are more sensitive to Cu toxicity than Yellow Perch, the liver accumulation threshold for Cu for Rainbow Trout and Sockeye Salmon are likely lower than the 50 mg/kg threshold of Yellow Perch [34]. These high concentrations of Cu have the potential to affect the health of individual fish and their populations in these waterbodies.

Concentrations of Se in Rainbow Trout from Quesnel Lake (approximately 0.5–3.5 mg/kg dw) are near the BCENV tissue guideline for the long-term average concentration of Se in muscle tissue (4 mg/kg dw) [13]. Selenium concentrations in muscle of Sockeye Salmon from Quesnel Lake and Rainbow Trout from Polley Lake are less than those < 2 mg/kg (dw).

5.3. What effects, if any, did the breach have on the biota (i.e., fish, benthic invertebrates, plankton, and amphibians) of Quesnel Lake and the other affected waterbodies (e.g., Polley Lake and Hazeltine Creek)?

Other than accumulation of metals by fish, only the abundance of benthic invertebrates and plankton is included in the database. However, differences in sample collection and uncertainties in taxonomy limited us to using presence/absence of families by waterbody rather than abundance at more specific taxonomic levels. Even then it is difficult to determine whether or not communities have been affected by the tailings breach because few waterbodies were sampled and only two lakes (Polley Lake and Quesnel Lake) were sampled for benthic invertebrates and only one lake (Polley Lake) was sampled for plankton pre- and post-breach. There was a shift in the benthic invertebrate community structures of Quesnel Lake and Polley Lakes post-breach towards metal-pollution tolerant families—Chironomidae, Chaoboridae, and Trombidiformes [35–40]. There was also a decrease in diversity (Shannon's diversity index) in Quesnel Lake. The decrease in diversity may be explained by a negative correlation between sediment Cu concentrations and diversity of benthic invertebrate fauna seen in other metal-contaminated sediment [41]. There was also a decrease in the diversity (Shannon's diversity index) of families. For plankton, there was a reduction in diversity in Polley Lake following the breach. However, there was an increase in species richness that might indicate ecological succession post-breach.

5.4. What data gaps are there spatially and by media (i.e., water, sediment, and biota) in the database?

Partial participation in the Mount Polley database by organizations possessing pre- and post-breach data limited the completeness and thus, utility of the database. In addition to incomplete participation, there are likely historic records that remain unaccounted for because they have been overlooked in the archives of organizations. Although there are more data on Mount Polley than our database reflects, our assessment of data gaps is only on the data received for the database. Overall, there were spatial, temporal, and media (water, sediment, and biota) gaps that limited our ability to compare pre- and post-breach conditions. Data gaps specific to each medium are explained in subsections 5.4.1–5.4.6.

5.4.1. Water

Water is the most extensively studied media in the database. Limnological measurements and metal concentrations were taken pre-breach (1987–2014, and 1989–1992 and 1995–2014, respectively) and post-breach (2014–2018 for both) from the widest spatial scale of any media. Despite the breadth of data, Quesnel Lake, Polley Lake, Hazeltine Creek, Edney Creek, and Quesnel River had enough samples for a pre- to post-breach comparison. Within Quesnel Lake, only the West Arm has enough samples for such a comparison. Even with enough samples, there is typically still a sampling bias toward a specific time (pre- or post-breach) or location (e.g., West Arm of Quesnel Lake) that hinders statistical analyses.

5.4.2. Sediment

Sediment is grossly underrepresented in the database compared to water, as it is an important source of contamination in these impacted waterbodies. The sediment samples for determining the concentrations of metals were taken within 50 km of the Mount Polley Mine pre- (1989, 1995, 1996, 2007, 2009, 2010, 2012, and 2013) and post-breach (2014–2016 and 2018). However, only Se was measured in the majority of pre-breach samples. Analyses of metal concentrations in sediment as related to the breach are nearly impossible given the nominal number of samples that are limited both temporally and spatially. Only the West Arm of Quesnel Lake was adequately sampled for a pre- to post-breach comparison, although there is a post-breach sampling bias.

5.4.3. Fish

Fish are the most represented biota in the database. Most fish data are on descriptive variables (e.g., species, sex, length, weight, age) rather than bioaccumulation of metals. The accumulation of metals in fish was examined pre-breach in Quesnel Lake (West, North, and East Arms), Polley Lake, and other regional waterbodies, and post-breach in Quesnel Lake (West and North Arms), Polley Lake, Bootjack Lake, Hazeltine Creek, and other regional waterbodies. However, all pre-breach data was limited to Cu (1991) and Se (1995, 2009, 2010, 2012, and 2013) with only full metal scans occurring post-breach (2014 and 2015). In addition, the fish species and tissues (whole body or specific physiologically sensitive tissues) analyzed differed greatly within the dataset. Thus, there are very few adequately sampled combinations of metal, waterbody, time (pre- and post-breach), fish species, and tissue that allow for meaningful comparisons.

5.4.4. Benthic invertebrate

There are fewer data on benthic invertebrates compared to fish, and most data are on community structure rather than bioaccumulation of metals. However, community structure data are from a smaller temporal and spatial area than these bioaccumulation data. Pre-breach (2007) samples were collected from Quesnel Lake, Edney Creek, and Hazeltine Creek, while post-breach samples were collected (2014 and 2015) from Quesnel River, Cariboo River, and smaller regional creeks. A few species were caught in plankton surveys of Quesnel Lake and Polley Lake. Spatial and temporal limitations are compounded by variation in taxonomy and sampling methods and effort over time.

Studies of accumulation of metals in benthic invertebrate tissue are limited both temporally, spatially, and by metals analyzed limiting the usefulness of the dataset. Pre-breach (2009, 2010, and 2013) samples were collected from Quesnel Lake, Polley Lake, Bootjack Lake, Edney Creek, Hazeltine Creek, Mount Polley Mine sites, and other regional waterbodies, while post-breach (2014–2016 and 2018) samples were collected from Quesnel Lake, Polley Lake, Bootjack Lake, Little Lake, Quesnel River, and Cariboo River. All pre-breach and the majority of post-breach samples were analyzed solely for Se in tissues. In addition, metals have been measured in bulk samples of invertebrates rather than individual species or invertebrates of the same feeding guild. Nonetheless, as different species and feeding guilds accumulate metals differently, concentrations of metals from bulk samples mask the true relationship between metal concentrations in the organism and the source of the metal (e.g., water, sediment, and diet)[42]. The choice to measure metals in bulk samples is likely due to the large mass (≥ 10 mL sample digestate) required by commercial laboratories for standard ICP-MS analyses. However, alternative analytical methods (GF-AAS and LA-ICP-MS) are available that require very small quantities of sample in comparison, which would allow for metals analysis at more specific taxonomic levels or feeding guilds.

5.4.5. Plankton

All plankton studies focused on community structure leaving the accumulation of metals by this important food source not assessed. Community surveys occurred pre- (1989, 2013, and 2014) and post-breach (2014–2017) in Polley Lake and Quesnel Lake. However, taxonomy and sampling methods and effort varied overtime preventing the use of abundance data and limiting analyses to the family level.

5.4.6. Amphibians

Amphibians are grossly underrepresented in the database. There are no data available for Quesnel Lake, Polley Lake, and Hazeltine Creek. There is only one study on amphibians that examined the accumulation of metals in tadpoles living in ponds on Polley Flats post-breach (2016).

5.5. What recommendations can be made for future action?

5.5.1. Database gaps in preexisting data

The Mount Polley Database is an important tool to understand the effects of the 2014 tailings impoundment breach and to improve monitoring and remediation in the affected area. In order to increase the utility of the database, the spatial, temporal, and media (i.e., water, sediment, and biota) gaps identified by the current analysis need to addressed (see subsection 5.4). We suggest encouraging participation by organizations that have not already contributed. Other organizations have collected limnological and biota data in the area that would be a valuable contribution to the database. Maybe instituting a database sharing agreement would convince wary potential contributors that their data could be part of the database without losing the opportunity to publish it. In addition, we suggest to continue working with already participating organizations to obtain other pertinent documents. There are many forgotten documents in organizations’ archives that contain pre-breach data and perhaps post-breach data that may help fill current data gaps.

5.5.2. Future data collection

Although a lot of data have been collected in the region pre- and post-breach, there are issues that prevent the usefulness of the data, including missing/improper sample identification and details, and dissimilar collection methods. In order to maximize data usage, we recommend establishing a standard sampling scheme for the long-term monitoring of water, sediment, and biota to be used at least within an organization. This should include the proper identification and detailing of each sample with pertinent information such as sample site, units, and sample contents. In addition, appropriate regional reference waterbodies away from the mine and breach-affected waterbodies, and reference regions within Quesnel Lake should be included in the standard sampling scheme, as both reference types are underrepresented in the current database.

5.5.3. Future research

Future research should focus on filling the gaps identified by this database analysis and engage contributors to work openly with one another so the science can take advantage of multiple perspectives. Major gaps in the database that should be addressed with future research include 1) pre- and post-breach metal exposure concentrations of fish based on otolith analysis via LA-ICP-MS, 2) invertebrate community structures pre- and post-breach based on paleolimnological surveys, 3) food web analysis, and 4) the accumulation and toxicity of metals from water and especially, sediment in Quesnel Lake and other affected waterbodies to aquatic biota. Toxicity work to date has focused primarily on metals in water and fish. Future toxicity research should 1) examine sediment toxicity to aquatic biota, 2) conduct full metal scans of biological tissues, and 3) measure metals in feeding guilds or species rather than bulk samples.

6. Conclusions

The Mount Polley Database was developed by BCENV and Pyle Consulting Inc. The database contains a lot of high-quality data. However, there are large temporal, spatial, and media gaps that limit the database's usefulness in our analyses. Based on the current dataset, many metal concentrations in water and sediment were already near or above BCENV's guidelines pre-breach, and our analyses suggest that the metal concentrations increased post-breach. To date, most water and sediment metal concentrations have since subsided to or near pre-breach levels. No effects-based data are represented in the database. However, the post-breach metal concentrations in water, sediment, and fish tissues in this database are consistent with concentrations in other studies that elicited metal toxicity (e.g., mortality, decreased growth, and chemosensory impairment) in aquatic biota [22,23,28,30,31,31,33,34,41]. Metals have been accumulated by Rainbow Trout and Sockeye Salmon in the West Arm of Quesnel Lake at levels known to be toxic to other species [31–33]. In addition to accumulation of metals, the diversity of benthic invertebrate communities seems to have declined post-breach. However, more data are required to confirm these invertebrate community relationships. Plankton and amphibians are too poorly represented in the database to determine whether the breach had any effects on their populations. Future work on the database and monitoring and research in the region should focus on filling the temporal, spatial, and media gaps highlighted in this report in order to better understand the effects of the 2014 tailings impoundment breach on aquatic systems, how to improve remediation efforts, and inform long-term monitoring plans.

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Appendix 1: Taxonomic changes used for the Mount Polley Database.

Original taxonomy	**New taxonomy for database**	**Rational for change in taxonomy**
Ababaena flos-aquae	*Aphanizomenon flosaquae*	Scientific name no longer accepted.
Acarina (Order)	Arachnida (Class)	Mites have been moved from Order Acarina and spilt between multiple orders. Records of mites in this order are listed as Class Arachnidia, the most specific taxon we are sure of.
Agmenellum	*Merismopedia*	Genus is no longer accepted.
UID *Anabaena* (Genus)	Nostocaceae (Family)	All species identified to Genus *Anabaena* in source files have been moved to two other Genera, *Dolichospermum* and *Aphanizomenon*. Reports of unidentified (UID) species in *Anabaena* are moved to Family Nostocaceae, the most specific taxonomic level shared by the two genera. Species specific changes are addressed below.
Anabaena affinis	*Dolichospermum affine*	Scientific name no longer accepted.
Anabaena circinalis	*Dolichospermum sigmoidem*	Scientific name no longer accepted.
Anabaena crassa	*Dolichospermum crassum*	Scientific name no longer accepted.
Anacystis limneticus	*Limnococcus limneticus*	Scientific name no longer accepted.
Aphanizomenon flos-aquae	*Aphanizomenon flosaquae*	Spelling of scientific name no longer accepted.

Aphanothece clathrate	*Anathece clathrata*	Scientific name no longer accepted.
Arthrodesmus	*Staurodesmus*	Genus is no longer accepted.
Calanoida/Cyclopoida	Hexanauplia (Class)	The orders *Cricotopus* and *Orthocladius* were reported as an order complex in source files. Records with this complex of Orders are instead listed as Class Hexanauplia, the most specific taxonomic level shared by the two orders.
UID *Ceratoneis*	*Hannaea*	One species, *Ceratoneis arcus*, was identified to this genus, but is now named *Hannaea arcus*. Reports of UID members of *Ceratoneis* were moved to *Hannaea*, as they are most likely *Hannaea arcus*. Species specific changes are addressed below.
Ceratoneis arcus	*Hannaea arcus*	Scientific name no longer accepted.
UID *Chroomonas*	*Komma*	All UID identified to *Chroomonas* were moved to *Komma*, as the only species belonging to the Genus *Chroomonas* that appears in this database, *C. acuta* has been moved to the Genus *Komma*. Thus, it is likely that the single report of an UID species in *Chroomonas* also belong to *Komma*. Species specific changes are addressed below.

Chroomonas acuta	*Komma caudata*	Scientific name no longer accepted.
Cricotopus/Orthocladius	Chironomidae (Family)	The genera *Cricotopus* and *Orthocladius* were reported as a genus complex in source files. Records with this genus complex are instead listed as Family Chironomidae, the most specific taxonomic level shared by the two genera.
Crucigenia	Scenedesmaceae (Family)	Three species of *Crucigenia* appear in source files: *Crucigenia crucifera, C. quadrata*, and *C. rectangularis.* Two of the three species, *C. curifera* and *C. rectangularis*, have been moved to the Genus *Willea*. Although *C. quadrata* is still accepted, reports of UID species in *Crucigenia* have been moved to Family Scenedesmaceae, the most specific taxonomic level shared by the two genera. Species specific changes are addressed below.
Crucigenia crucifera	*Willea crucifera*	Scientific name no longer accepted.
Crucigenia rectangularis	*Willea rectangularis*	Scientific name no longer accepted.
Cyclocalyx	*Euglesa*	Genus no longer accepted.
Cyclotella bodanica	*Lindavia bodanica*	Scientific name no longer accepted.
Cymbella	Cymbellaceae (Family)	Two species of *Cymbella* appear in source files: *Cymbella flexella* and

		C. minuta, which have been moved to the genera *Achnanthes* and *Encyonema*, respectively. Reports of UID species in *Cymbella* were moved to Family *Cymbellaceae*, the most specific taxonomic level shared by the two genera. Species specific changes are addressed below.
Cymbella flexella	*Achnanthes flexella*	*Achnanthes flexella* is the more accepted synonym for *Cymbella flexella* and appeared almost exclusively in the reports used for this database. The one record of *C. flexella* was changed to *A. flexella*. Species specific changes are addressed below.
Cymbella minuta	*Encyonema minutum*	Scientific name no longer accepted.
Diceras phaseolus	*Bitrichia phaseolus*	Scientific name no longer accepted.
Gloeocystis	*Sphaerellocystis*	Genus is no longer accepted.
Gomphonema constrictum	*Gomphonema truncatum*	Scientific name no longer accepted.
Kephyrion / Pseudokephyrion	Dinobryaceae (Family)	The genera *Kephyrion* and *Pseudokephyrion* were reported as a genus complex in source files. Records with this genus complex are instead listed as Family Dinobryaceae, the most specific taxonomic level shared by the two genera.

Lyngbya	*Planktolyngbya*	Genus is no longer accepted.
UID *Melosira*	*Aulacoseria*	Three species of *Melosira* appear in source files: *Melosira granulata*, *M. italica*, and *M. varians*. *Melosira varians* is still accepted as the correct taxonomy. However, *M. granulata* and *M. italic* have been moved to the Genus *Aulacoseria*. Reports of UID species in *Melosira* were moved to *Aulacoseria*, as there is a higher probability that they are *A. italica* than *M. varians* based on the number of records. Species specific changes are addressed below.
Melosira granulata	*Aulacoseira granulata*	Scientific name no longer accepted.
Melosira italica	*Aulacoseira italica*	Scientific name no longer accepted.
Nemata (Phylum)	Nematoda (Phylum)	Phylum no longer accepted.
Nephrocytium	*Oonephris*	One species, *Nephrocytium ecdysiscepanum*, was identified to this genus, but is now named *Oonephris obesa*. Although *Nephrocytium* is still accepted as a genus. Reports of UID species in *Nephrocytium* were changed to *Oonephris* as there is a higher probability that they *O. obesa*. Species specific changes are addressed below.

Nephrocytium ecdysiscepanum	*Oonephris obesa*	Scientific name no longer accepted.
UID Ochromonadales (Order)	Chromulinales (Order)	Reports of unidentified members of the Order Ochromonadales were listed to the Order Chromulinales, as the species that appear in this database have been moved to Chromulinales. Thus, it is likely that the UID species also belong to Chromulinales.
Pediastrum	*Pseudopediastrum*	Genus is no longer accepted.
Pennales (Order)	Bacillariophyceae (Class)	Order Pennales is no longer accepted. Records with this order in the source files are instead listed as Class Bacillariophyceae, the most specific taxonomic level that we can be certain of.
UID *Peridinium*	*Parvodinium*	The one species, *Peridinium inconspicuum,* identified to the genus Peridinium in source files, has been changed to *Parvodinium*. Reports of UID species in *Peridinium* were changed to *Parvodinium* as there is a higher probability that they are *Parvodinium inconspicuum.* Species specific changes are addressed below.
Peridinium / Glenodinium	Peridiniaceae (Family)	The genera *Peridinium* and *Glenodinium* were reported as a complex in the source files. Records

		with this genus complex are instead listed as Family Peridiniaceae, the most specific taxonomic level shared by the two genera.
Peridinium inconspicuum	*Parvodinium inconspicuum*	Scientific name no longer accepted.
Quadrigula	*Gregiochloris*	Two species of *Quadrigula* appear in source files: *Quadrigula closterioides* and *Q. lacustris*. *Quadrigula closterioides* is still accepted as the correct. However, *Q. lacustris* has been moved to *Gregiochloris*. Reports of UID species in Quadrigula are listed as Family Selenastraceae, the most specific taxonomic level shared by the two genera.
Quadrigula lacustris	*Gregiochloris lacustris*	Scientific name no longer accepted.
Rhoicosphenia curvata	*Rhoicosphenia abbreviata*	Scientific name no longer accepted.
Scenedesmus	*Desmodesmus*	Two species of *Scenedesmus* appear in source files: *Scenedesmus arcuatus* and *Scenedesmus denticulatus*. *Scenedesmus arcuatus* is still accepted as the correct. However, *S. denticulatus* has been changed to the *Desmodesmus denticulatus*. Organisms identified as *Scenedesmus sp.* were left as such as there is an equal probability that they are *S. arcuatus* and *D. denticulatus* based on the number of

		records. Species specific changes are addressed below.
Scenedesmus denticulatus	*Desmodesmus denticulatus*	Scientific name no longer accepted.
Selenastrum	*Monoraphidium*	Only one species was identified to Genus *Selenastrum, Selenastrum minutum,* was changed to the Genus *Monoraphidium.* Organisms identified as *Selenastrum sp.* were changed to *Monoraphidium* as there is a high probability that they are *Monoraphidium minutum.* Species specific changes are addressed below.
Selenastrum minutum	*Monoraphidium minutum*	Scientific name no longer accepted.
Synedra actinastroides	*Nitzschia holsatica*	Scientific name no longer accepted.
Tubificidae (Family)	Naididae (Family)	Family no longer accepted.

Appendix 2: Sampling intensity by waterbody, sample site, and media (i.e., water [limnology and water metals], sediment, and biota) sampled.

		Pre-breach				Post-breach			
Waterbody	**SampleSiteID**	**Limnology**	**Water metals**	**Sediment**	**Biota**	**Limnology**	**Water metals**	**Sediment**	**Biota**
Bootjack Creek	526	0	0	0	2	0	0	0	0
Bootjack Lake	341	0	0	0	1	0	0	0	0
Bootjack Lake	365	0	11	0	2	0	0	0	0
Bootjack Lake	386	1	1	1	0	0	0	0	0
Bootjack Lake	397	0	0	0	0	0	1	0	0
Bootjack Lake	428	1	0	0	0	0	0	0	0
Bootjack Lake	429	1	0	0	0	0	0	0	0
Bootjack Lake	453	6	3	0	0	0	0	0	0
Bootjack Lake	454	1	0	0	0	0	0	0	0
Cariboo River	28	0	0	0	0	3	3	0	0
Cariboo River	29	0	0	0	0	3	2	0	0
Cariboo River	73	0	0	0	0	0	1	0	0
Cariboo River	77	0	0	0	0	2	2	0	0
Cedar Creek	236	0	0	0	0	2	0	0	0
East Side Pond	272	0	0	0	0	1	0	0	0
Edney Creek	51	0	0	0	0	20	53	0	0
Edney Creek	317	0	1	0	0	0	0	0	1

Edney Creek	319	1	0	1	1	0	0	0	0
Edney Creek	320	1	1	1	2	0	0	0	0
Edney Creek	356	1	1	0	1	0	0	0	0
Edney Creek	357	10	0	1	1	0	24	0	0
Edney Creek	360	0	0	0	1	0	0	0	0
Edney Creek	367	0	0	0	2	0	0	0	0
Edney Creek	368	0	0	1	0	0	0	0	0
Edney Creek	369	1	0	1	1	0	0	0	0
Edney Creek	370	1	0	1	0	0	0	0	0
Edney Creek	371	0	0	0	1	0	0	0	0
Edney Creek	372	1	0	0	1	0	0	0	0
Edney Creek	505	1	18	0	0	46	9	0	1
Fish Lake	479	1	1	0	0	0	0	0	0
Fraser River	285	0	0	0	0	0	0	0	0
Fraser River	287	0	0	0	0	0	0	0	1
Fraser River	288	0	0	0	0	1	0	0	2
Fraser River	289	0	0	0	0	0	0	0	0
Fraser River	506	0	0	0	0	1	0	0	0
Frypan Lake	279	0	0	0	3	1	1	0	0
Frypan Lake	434	1	0	0	0	0	0	0	0
Frypan Lake	437	1	0	0	0	0	0	0	0

Frypan Lake	448	2	0	0	0	0	0	0	0
Gavin Lake	67	0	0	0	0	2	2	1	0
Hazeltine Creek	3	277	272	1	2	0	0	0	1
Hazeltine Creek	50	0	0	0	0	3	4	0	0
Hazeltine Creek	59	0	0	0	0	32	33	0	0
Hazeltine Creek	60	0	0	0	0	1	0	0	0
Hazeltine Creek	81	2	0	0	0	0	0	0	0
Hazeltine Creek	87	0	0	0	0	61	57	0	0
Hazeltine Creek	227	0	0	0	0	1	1	0	0
Hazeltine Creek	229	1	2	0	0	0	0	0	0
Hazeltine Creek	232	0	0	0	0	4	0	0	0
Hazeltine Creek	233	0	0	0	0	0	1	0	0
Hazeltine Creek	321	0	0	0	1	0	0	0	0
Hazeltine Creek	334	0	0	1	1	0	0	0	0
Hazeltine Creek	335	0	0	1	2	0	0	0	0
Hazeltine Creek	343	0	0	0	1	0	0	0	0
Hazeltine Creek	351	0	0	0	1	0	0	0	0
Hazeltine Creek	358	0	0	1	2	0	0	0	0

Hazeltine Creek	361	0	1	3	2	0	0	0	0
Hazeltine Creek	374	0	0	2	0	0	0	0	0
Hazeltine Creek	375	0	0	1	1	0	0	0	0
Horsefly River	328	0	0	0	1	0	0	0	0
Horsefly River	329	0	0	0	1	0	0	0	0
Horsefly River	330	0	0	0	4	0	0	0	0
Horsefly River	332	0	0	0	1	0	0	0	0
Horsefly River	337	0	0	0	18	0	0	0	0
Horsefly River	497	1	0	0	0	0	1	0	0
Jacobie Creek	394	1	0	0	0	0	0	0	0
Little Horsefly River	340	0	0	0	3	0	0	0	0
Little Lake	396	0	0	0	0	1	1	1	0
Main embankment seepage collection pond	381	1	0	0	0	0	0	0	0
Mine Drainage Creek	467	1	1	0	0	0	0	0	0
Mons Creek	311	0	0	0	0	0	0	0	0
Morehead Creek	390	1	0	0	0	0	0	0	0
Morehead Creek	523	0	0	0	2	0	0	0	4
MPMC	66	0	0	0	0	1	0	3	2
MPMC	93	0	0	0	0	1	0	0	0

MPMC	269	0	0	0	0	0	1	0	0
MPMC	270	0	0	0	0	2	0	0	0
North Dump Creek	382	1	0	0	0	0	0	0	0
Polley Flats	65	0	0	0	0	1	4	1	0
Polley Flats	226	0	0	0	0	0	1	0	0
Polley Flats	271	0	0	0	0	1	0	0	0
Polley Flats	276	0	0	0	0	1	0	0	0
Polley Lake	1	4	5	1	1	13	14	0	0
Polley Lake	2	1	4	0	1	1	15	0	14
Polley Lake	26	0	0	0	0	0	1	0	0
Polley Lake	228	0	0	0	0	3	1	0	0
Polley Lake	231	1	1	0	0	0	0	0	0
Polley Lake	310	0	0	0	1	0	0	0	0
Polley Lake	342	0	0	0	1	0	0	0	0
Polley Lake	364	0	0	0	10	0	0	0	0
Polley Lake	373	0	0	2	1	0	0	0	0
Polley Lake	384	15	0	4	0	0	0	0	0
Polley Lake	385	1	2	0	0	0	0	0	0
Polley Lake	398	0	0	0	0	1	1	0	1
Polley Lake	420	1	0	0	0	0	0	0	0
Polley Lake	425	1	0	0	0	0	0	0	0

Polley Lake	426	1	0	0	0	0	0	0	0
Polley Lake	441	1	0	0	0	0	0	0	0
Polley Lake	443	1	0	0	0	0	0	0	0
Polley Lake	445	1	0	0	0	0	0	0	0
Polley Lake	451	4	5	0	0	0	1	0	0
Polley Lake	452	13	0	0	0	0	0	0	0
Polley Lake	463	1	1	0	0	0	0	0	0
Polley Lake	522	0	0	0	0	0	0	0	0
Polley Lake	528	0	0	0	1	0	0	0	0
Polley Lake	529	0	0	0	1	0	0	0	0
Polley Lake	530	0	0	0	0	0	0	0	0
Quesnel Lake	4	34	67	0	0	0	0	0	4
Quesnel Lake	9	0	0	0	0	6	6	0	5
Quesnel Lake	16	0	0	0	0	1	1	0	0
Quesnel Lake	17	0	0	0	0	3	20	1	0
Quesnel Lake	18	0	0	0	0	1	0	2	2
Quesnel Lake	19	0	0	0	0	5	1	0	0
Quesnel Lake	23	0	0	0	0	1	1	0	8
Quesnel Lake	24	0	0	0	2	0	1	1	0
Quesnel Lake	25	0	0	0	0	0	1	0	3
Quesnel Lake	33	0	0	0	0	3	1	0	4

Quesnel Lake	34	0	0	0	0	0	1	0	1
Quesnel Lake	36	0	0	0	0	0	1	0	1
Quesnel Lake	38	0	0	0	0	1	0	0	0
Quesnel Lake	39	0	0	0	0	0	0	0	0
Quesnel Lake	45	0	0	0	0	0	0	0	3
Quesnel Lake	49	1	1	0	0	0	0	0	2
Quesnel Lake	52	0	0	0	0	17	24	0	0
Quesnel Lake	53	0	0	0	0	24	56	0	0
Quesnel Lake	54	0	0	0	0	9	11	0	0
Quesnel Lake	55	0	0	0	0	6	11	0	0
Quesnel Lake	56	0	0	0	0	1	3	0	0
Quesnel Lake	57	0	0	0	0	3	1	0	0
Quesnel Lake	61	0	0	0	0	0	1	0	0
Quesnel Lake	62	0	0	0	0	1	5	0	0
Quesnel Lake	63	0	0	0	0	1	2	0	0
Quesnel Lake	64	0	0	0	0	27	21	0	0
Quesnel Lake	72	0	0	0	0	3	3	0	1
Quesnel Lake	92	0	0	0	0	0	1	0	0
Quesnel Lake	96	0	0	0	0	1	1	0	0
Quesnel Lake	103	0	0	0	0	0	1	0	0
Quesnel Lake	109	0	0	0	0	1	5	0	0

Quesnel Lake	110	1	0	0	0	1	0	0	0
Quesnel Lake	112	0	0	0	0	0	1	0	0
Quesnel Lake	117	0	0	0	0	0	1	0	0
Quesnel Lake	119	0	0	0	0	6	2	0	0
Quesnel Lake	134	0	0	0	0	1	0	0	0
Quesnel Lake	135	0	0	0	0	1	0	0	0
Quesnel Lake	136	0	0	0	0	1	1	0	0
Quesnel Lake	137	0	0	0	0	1	1	0	0
Quesnel Lake	141	0	0	0	0	0	1	0	0
Quesnel Lake	142	0	0	0	0	1	1	0	0
Quesnel Lake	143	0	0	0	0	8	5	0	0
Quesnel Lake	144	0	0	0	0	6	6	0	0
Quesnel Lake	145	0	0	0	0	4	0	0	0
Quesnel Lake	146	0	0	0	0	1	0	0	0
Quesnel Lake	147	0	0	0	0	3	0	0	0
Quesnel Lake	148	0	0	0	0	2	0	0	0
Quesnel Lake	149	0	0	0	0	1	0	0	0
Quesnel Lake	153	0	0	0	0	1	1	0	0
Quesnel Lake	157	0	0	0	0	2	3	0	0
Quesnel Lake	160	0	0	0	0	1	0	0	0
Quesnel Lake	163	0	0	0	0	2	0	0	0

Quesnel Lake	164	0	0	0	0	7	4	0	0
Quesnel Lake	168	0	0	0	0	1	1	0	0
Quesnel Lake	169	0	0	0	0	1	0	0	0
Quesnel Lake	170	0	0	0	0	4	2	0	0
Quesnel Lake	179	0	0	0	0	3	2	0	0
Quesnel Lake	192	0	0	0	0	5	0	0	0
Quesnel Lake	195	0	0	0	0	1	0	0	0
Quesnel Lake	196	0	0	0	0	1	0	0	0
Quesnel Lake	197	0	0	0	0	1	0	0	0
Quesnel Lake	201	0	0	0	0	2	0	0	0
Quesnel Lake	204	0	0	0	0	1	0	0	0
Quesnel Lake	209	0	0	0	0	1	0	0	0
Quesnel Lake	212	0	0	0	0	1	0	0	0
Quesnel Lake	263	0	0	0	0	0	0	1	0
Quesnel Lake	265	0	0	0	0	0	0	1	0
Quesnel Lake	266	0	0	0	0	1	0	0	0
Quesnel Lake	291	0	0	0	0	0	0	0	1
Quesnel Lake	296	0	0	0	0	0	0	0	4
Quesnel Lake	297	0	0	0	0	0	0	0	1
Quesnel Lake	339	0	0	0	4	0	0	0	0
Quesnel Lake	363	0	0	0	5	0	0	0	0

Quesnel Lake	366	0	0	0	7	0	0	0	0
Quesnel Lake	389	1	1	1	0	0	0	0	0
Quesnel Lake	399	0	0	0	0	1	1	1	1
Quesnel Lake	400	0	0	0	0	1	1	1	1
Quesnel Lake	402	0	0	0	0	0	1	1	1
Quesnel Lake	459	12	0	0	0	0	0	0	0
Quesnel Lake	460	24	0	0	0	0	0	0	0
Quesnel Lake	461	18	0	0	0	0	0	0	0
Quesnel Lake	462	9	0	0	0	0	0	0	0
Quesnel Lake	504	1	0	0	0	0	1	0	0
Quesnel River	5	0	0	0	0	2	2	0	0
Quesnel River	10	0	0	0	0	1	3	0	0
Quesnel River	11	0	0	0	0	0	1	0	0
Quesnel River	12	0	0	0	0	0	1	0	0
Quesnel River	13	0	0	0	0	0	1	0	0
Quesnel River	14	0	0	0	0	0	7	0	0
Quesnel River	15	0	0	0	0	1	2	0	1
Quesnel River	27	0	0	0	0	13	17	0	0
Quesnel River	41	0	0	0	0	2	2	0	2
Quesnel River	48	0	0	0	5	0	0	0	2
Quesnel River	323	0	0	1	4	0	0	0	0

Quesnel River	324	0	0	0	3	0	0	0	0
Quesnel River	325	0	0	0	7	0	0	0	0
Quesnel River	326	0	0	0	10	0	0	0	0
Quesnel River	327	0	0	0	16	0	0	0	0
Quesnel River	517	2	3	0	0	0	0	0	0
Trio Lake	362	0	0	0	1	0	0	0	0
Trio Lake	404	1	0	0	0	0	0	0	0
Unknown	298	0	0	0	1	0	0	0	1
Whiffle Creek	359	1	1	0	1	0	0	0	0