

# Potential effects and impacts of a coal spill on sensitive aquatic habitat: a weight-of-evidence sediment quality assessment

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## ABSTRACT

On 11 January 2014, a Canadian Pacific Railway train derailed on the Canadian National Railway Company's Yale Subdivision, Mile 122.7, in Burnaby, British Columbia, Canada. This derailment resulted in the partial release of metallurgical coal from three rail cars into, and adjacent to, Silver Creek. Following the derailment and subsequent spill, a comprehensive coal recovery program was implemented. As part of the program, coal deposits were removed from the Silver Creek mainstem in the right-of-way during the stabilization work. A total of approximately 143 tonnes of mixed coal, organic and mineral fines were removed during this program. Subsequently, using a weight-of-evidence sediment quality triad approach, a two-year Aquatic Impact Assessment was conducted to evaluate whether the remaining residual coal in Silver Creek and Burnaby Lake presented the potential for impact to the aquatic environment. Lines-of-evidence (LOEs) were evaluated, including sediment chemistry, sediment toxicity, bioaccumulation potential and coal content. The majority of the data from exposed sampling locations indicated that there was low potential for impact, based on the assessed LOEs. Hence, given the overall low potential for residual impacts from the coal deposits in the Silver Creek–Burnaby Lake ecosystem, no further clean up or monitoring was recommended.

**Key words** | aquatic environment, bioaccumulation potential, coal, sediment, toxicity, weight-of-evidence approach

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## INTRODUCTION

### Ecological effects of coal

Almost a quarter of the world's energy is produced by coal (Baker 2013). Canada is a major producer of metallurgical (or coking) coal, which originates mainly from bituminous coal (Baker 2013). Given its significance to Canada's resource industry, an understanding of the impacts that raw or unburnt coal could have on the surrounding environment is crucial. There are a number of ways in which coal can enter aquatic ecosystems, including: erosion of exposed, undisturbed coal seams; losses from coarse coal refuse stockpiles at coal mining operations; fugitive dust and incidental spills of coal during transportation (Goldberg *et al.*

1977, 1978; Ferreira *et al.* 2003; Ahrens & Morrisey 2005; U.S. Bureau of Land Management 2009; Baruya 2012).

Once the coal is introduced into the environment, various potential effects are possible, specifically: physical effects that can change the utilization of natural space (i.e., habitat modification) and chemical effects that can disrupt the physiology of aquatic organisms (Ahrens & Morrisey 2005; Hapke *et al.* 2019). The main factors that determine the impacts of unburnt coal on the freshwater environment are the relative breakdown and exposure time in the surrounding environment (Ahrens & Morrisey 2005).

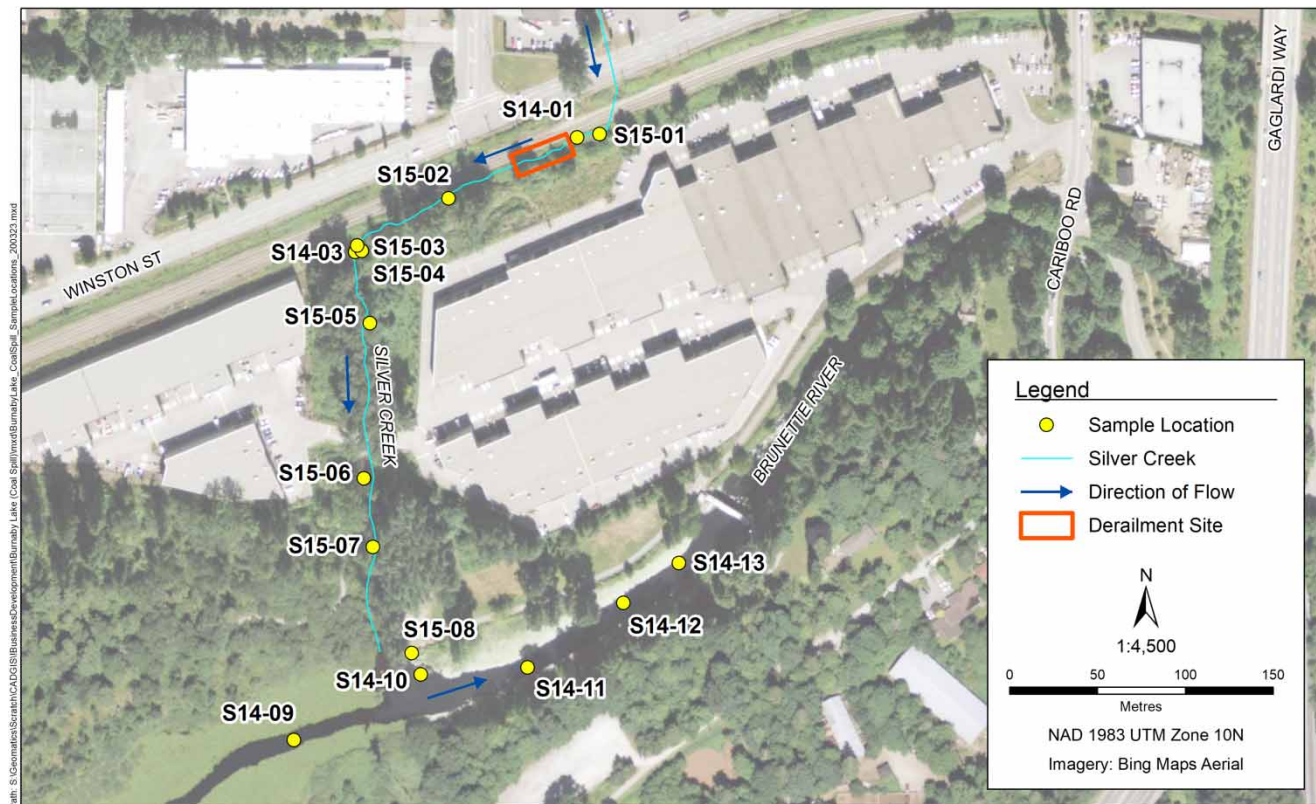
Much of the existing research has focused on the impacts of coal subsequent to processing; there is a relative lack of

scientific research on the effects of unburnt coal on freshwater ecosystems. Studies on smaller coal particles have proved useful. Contact time is a major factor relating to chemical effects due to the presence of unburnt coal (Ahrens & Morrisey 2005). Over time, coal breaks down into smaller particles, thereby increasing the surface area; this, in turn, increases the likelihood of bound chemicals being leached out of the coal matrix (Ghosh et al. 2000, 2001), released into the environment and taken up by biota (Eisler 1987; Clements et al. 1994; Talley et al. 2002). Moreover, a relationship between the particle size, the surface area, and the relative rate of chemical release from the coal has been established (Davis & Boegly 1981; Ghosh et al. 2001). The mineral content of the coal (and the chemical elements bound within the carbon matrix) and physical characteristics of the surrounding environment (e.g., pH and temperature) can also have an impact on the resulting speciation of chemical constituents. Moreover, the bioavailability of the chemicals released from unburnt coal is also heavily influenced by these factors.

### Spill incident

On 11 January 2014, a Canadian Pacific Railway train derailed on the Canadian National Railway Company's (CN) Yale Subdivision, Mile 122.7, in Burnaby, British Columbia, Canada (Figure 1). This derailment resulted in the partial release of metallurgical coal from three rail cars into, and adjacent to, Silver Creek. From the derailment site, Silver Creek flows approximately 350 m before entering Burnaby Lake (an urban lake in metropolitan Vancouver, British Columbia, Canada) and 200 m upstream of the Cariboo Dam. From the Cariboo Dam, the Brunette River flows approximately 6 km before entering the Fraser River, the largest watershed in British Columbia.

Following the derailment and subsequent spill, a comprehensive coal recovery program was implemented. As part of the program, coal deposits in lower Silver Creek, the off-channel habitat in Silver Creek located immediately south of the Cariboo Business Park Driveway, and parts of



**Figure 1** | Aerial view of Silver Creek and Burnaby Lake, indicating sampling locations. Locations designations: 'S' refers to sediment samples, '14' and '15' refer to sampling year (2014 or 2015) and '-##' refers to the sample location, numbered from upstream to downstream. S14-01, S15-01 and S14-09 are reference stations.

Burnaby Lake into which Silver Creek discharges, were removed using a vacuum-truck system and/or hand tools. Coal was removed from the Silver Creek mainstem in the right-of-way during the stabilization work and the works conducted during the coal recovery program. A total of approximately 143 tonnes of mixed coal, organic and mineral fines were removed during the whole program. Based on identified performance criteria, it was considered impractical to remove additional coal without concomitant removal of significant volumes of native substrates and potential disturbance of sensitive riparian habitats.

### Environmental setting

Burnaby Lake is an urban shallow water body located in Burnaby Lake Regional Park in the City of Burnaby, British Columbia, in the Greater Vancouver Area (Li et al. 2009). The lake is part of the Brunette Watershed, which comprises

Deer Lake, Still Creek and the Brunette River (ENKON 2002; Figure 2). Silver Creek – the watercourse into which the derailment occurred – is a first-order tributary to Burnaby Lake's northeast shoreline where it transitions into the Brunette River. Burnaby Lake comprises various habitats; for example, where Still Creek empties into Burnaby Lake, it is characterized as a riparian corridor (Sampson & Watson 2004). The surrounding area of Burnaby Lake constitutes several vegetated habitat types, including: mixed forest habitat, grass, fern and shrub-dominant habitat, grass-rush wetland, an important habitat for various endangered plant species in British Columbia, which is also part of the Burnaby Lake and the Brunette Watershed area (Golder et al. 1997).

Aquatic species within the watershed include both fish and invertebrate species. Fish species in Burnaby Lake include Brassy Minnow, Carp, Cutthroat Trout, Northern Pikeminnow, Peamouth Chub, Prickly Sculpin, Rainbow

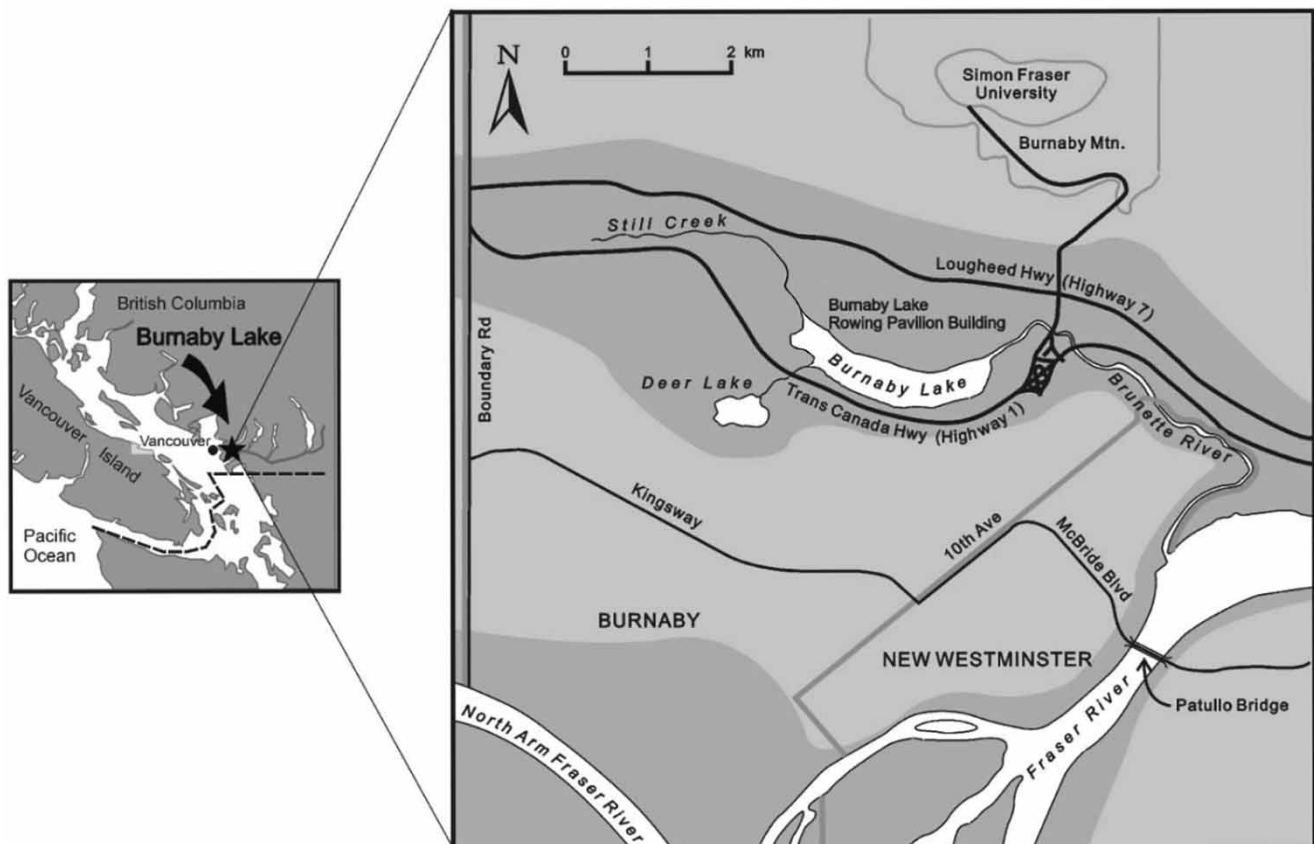


Figure 2 | Burnaby Lake and neighboring water bodies (from Brewer & Belzer 2001).

Trout and Three-spine Stickleback (Metro Vancouver 2001; Haid 2005; FISS 2014). The Brunette River also supports Chum and Coho Salmon, Steelhead, Coastal Cutthroat Trout and Nooksack Dace (FISS 2014). Numerous aquatic macroinvertebrate species in the watershed have been documented in the literature. As part of the Environmental Assessment (EA) for the Rejuvenation of Burnaby Lake, collections of benthic invertebrates included high densities of nematodes, tubificid oligochaetes, copepods, cladocerans and midges (ENKON 2002). Moreover, collections of planktonic invertebrates included high densities of populations of several genera, including (predominantly): *Daphnia* spp., *Cyclops* spp., *Diaptomus* spp. and rotifers (e.g., *Felina* sp.) (ENKON 2002).

### Aquatic Impact Assessment of sediments using a weight-of-evidence approach

This study involved a multi-year Aquatic Impact Assessment (AIA) of the potentially-exposed receiving sediment environments in Silver Creek and Burnaby Lake, conducted specifically to evaluate residual impacts from unrecovered coal downstream of the spill area. While not discussed herein, water quality monitoring was also conducted as part of the coal recovery program. The results indicated that all relevant chemical parameters measured in the watershed were within applicable water quality guidelines, with some exceptions not deemed to be spill-related.

The investigation and evaluation of the receiving aquatic environment were designed to focus on potential short- and long-term sediment impacts. A weight-of-evidence (WOE) approach (Chapman *et al.* 2002), focusing on risks to sediment quality, was used to identify any potential significant effects on resident aquatic biota in the exposed areas of Silver Creek and Burnaby Lake. This WOE approach integrates the results from the evaluations of sediment chemistry, sediment toxicity, bioaccumulation potential and coal particle content; each of the evaluation endpoints is considered as a distinct line of evidence (LOE) in this approach.

An LOE is any pairing of exposure and effects measures that provides evidence for the evaluation of a specific assessment endpoint (Environment Canada 2012). Each LOE consists of an assessment endpoint and a measurement

endpoint. Assessment endpoints are the explicit expression of the values to be protected in a risk (or impact) assessment (Suter *et al.* 2000). These assessment endpoints include the quality of sediment, such that coal-related impacts do not result in adverse effects to the population, the health of the aquatic community, and/or the function of the benthic community as a food source for birds, mammals, reptiles, fish and amphibians in the area. A measurement endpoint describes exposure to a stressor for, or an effect on, a specific receptor (i.e., organism) of concern. Integrating the results of these LOEs allows for a transparent assessment and provides a means of determining the potential for adverse effects/impacts.

The results and conclusions from these LOEs (e.g., exceedance/non-exceedance of sediment quality guidelines, potential acute or chronic toxicity and/or demonstrated bioaccumulation potential) would provide a basis for whether or not a further evaluation of biological community health or other components may be recommended.

### Rationale, purpose and objectives

Based on the chemical characteristics of the spilled product (i.e., raw, washed metallurgical coal), the focus of this AIA was on the residual (i.e., post-recovery) impacts to sediment and resident aquatic biota. A WOE approach was applied, in order to consider any potential impacts of coal product constituents (and by-products) through toxicity to sediment-based receptors, which can also indirectly exert effects – via ingestion of lower trophic-level organisms – to upper trophic-level biota (e.g., amphibians, water birds and riparian species).

## METHODS

An assessment of residual aquatic sediment impacts to Silver Creek and Burnaby Lake due to the coal spill was conducted in May and June 2014, subsequent to initial significant clean up and restoration efforts. A year later, in May 2015, a follow-up monitoring evaluation was conducted to assess the potential recovery of aquatic receptors in Silver Creek and to investigate the recommendations from the previous year's assessment.

## Sediment sampling

*Spring 2014 Assessment.* Prior to sediment sampling, a reconnaissance visit to Silver Creek and Burnaby Lake in the vicinity of the derailment site was undertaken; visible spilled coal was noted at the first 'bend' of the creek (Figure 1) and where localized physical remediation was conducted. Initial sediment sampling was conducted using (1) hand trowels (for Silver Creek sites) and (2) an Ekman grab sampler (for Burnaby Lake sites) at seven stations on two occasions: 30 and 31 May and 9 June 2014, approximately 4.5 months subsequent to the spill. Remediation activities had been concluded approximately 1–1.5 months prior to the spring 2014 sediment sampling program. Samples were collected upstream, downstream and within the spill-affected (i.e., 'exposure') areas in Silver Creek and Burnaby Lake, using a gradient sampling design. Two reference stations (i.e., S14-01 and S14-09) and five exposure stations (i.e., S14-03, S14-10, S14-11, S14-12 and S14-13) allowed for spatial comparisons of both exposed and unexposed areas (Figure 1).

*Spring 2015 Assessment.* The aim of the 2015 sampling program was to focus on Silver Creek and to fill in the gaps in the gradient, rather than replicate the sampling conducted in 2014. As part of the follow-up monitoring evaluation, prior to sediment sampling, a follow-up reconnaissance site visit of Silver Creek was undertaken; visible coal was still noted at the bend of the creek and where localized physical remediation was conducted. On 26 May 2015, sediment sampling focused on an area within Silver Creek, and samples were collected using hand trowels only. Eight sampling stations were selected: one upstream of the derailment site (i.e., station S15-01), one downstream of the derailment site within the extent of channel modifications undertaken as part of the clean-up zone (i.e., station S15-02), five downstream along Silver Creek (i.e., stations S15-03 to S15-07) and one downstream on the north bank of Burnaby Lake (i.e., station S15-08) offshore from Turtle Beach and within the 2014 coal recovery area. Sediment sampling stations S15-03 and S15-04 were located beside one another (i.e., within 1 m) at the bend of Silver Creek; station S15-04 was the location of the previously visible coal (remediated subsequent to the reconnaissance site visit). While not wetted at the time of the sampling, S15-04

was within the riparian zone and is generally under water during the wet season. All other stations were either within the wetted banks of the creek (i.e., stations S15-03 to S15-07) or below the water level of Burnaby Lake (i.e., station S15-08) (Figure 1).

*Submission of Samples for Chemical Analyses.* For both sampling years, sediment was collected from all sampling stations for chemical analyses at the following accredited laboratories: AGAT Laboratories (Burnaby, BC, Canada) in 2014 and Maxxam Analytics (Now Bureau Veritas Laboratories, Burnaby, BC, Canada) in 2015. Analyses included the following parameters: total organic carbon (TOC), particle size, metals, pH and polycyclic aromatic hydrocarbons (PAHs).

*Quality Assurance/Quality Control Measures.* All quality assurance/quality control measures achieved acceptable regulatory standards (see Supplementary Materials for additional details).

## Comparison criteria for sediment quality

The chemical LOE involved the comparison of sediment chemistry to applicable sediment quality criteria, in order to determine if concentrations exceeded regulatory guidelines and standards. Specifically, the results were compared to the Canadian Council of Ministers of the Environment (CCME) Interim Sediment Quality Guidelines (ISQGs) and Probable Effects Levels (PELs) (CCME 2005), and the BC MOE Sediment Quality Guidelines for the Protection of Aquatic Life consisting of Lower and Upper Working Quality Guidelines – Sediment (SWQG) (BC MOE 2013).

## Sediment, leachate and porewater toxicity testing

In both 2014 and 2015 assessments, sediments collected from selected sampling stations were evaluated for sediment toxicity. In 2014, testing was conducted at Nautilus Environmental (Burnaby, BC, Canada), using sediments collected from sampling stations S14-01, S14-03, S14-09, S14-10 and S14-12, and in 2015, testing was conducted at Maxxam Analytics (Burnaby, BC, Canada) using sediments collected from sampling stations S15-01, S15-03, S15-05, S15-07 and S15-08.

Toxicity test species were selected to align – both ecologically and/or taxonomically – with those found in the receiving environment (see Environmental Setting section). Specifically, fish (Rainbow Trout) and invertebrate test species (e.g., midges and mudworms) described below were deemed to be adequate surrogates for those species reported to reside in the Burnaby Lake aquatic ecosystem.

During both programs, the sediment toxicity tests undertaken were: the 10-day *Chironomus dilutus* (freshwater midge fly larvae) growth and survival test (Environment Canada 1997); the 14-day *Hyaella azteca* (freshwater amphipod crustacean) growth and survival test (Environment Canada 2013) and the 28-day *Lumbriculus variegatus* (freshwater mudworm) survival and bioaccumulation test (US EPA 2000).

During the 2014 program only (at all sampling locations), two additional tests were conducted: a leachate test and a sediment porewater test. The 96-h rainbow trout acute survival test (Environment Canada 2007a) (the leachate test) was conducted using a modified methodology involving test water that was leached from collected sediments. For these tests, the sediment ‘leachate’ was generated using under-gravel filters; prior to toxicity testing, the under-gravel filters were placed at the bottom of each 20 L aquaria and 3 kg of sample was placed on top of the filters. The 72-h *Pseudokirchneriella subcapitata* (green alga) acute growth inhibition test (Environment Canada 2007b) was conducted to evaluate the toxicity of sediment porewater. Sediment porewater was obtained by centrifuging an aliquot of sediment at 1500 rpm for 15 min under refrigerated conditions. The resulting overlying porewater was carefully decanted and used immediately to conduct the alga test. Given the size of green algal cells and their presence as periphyton in freshwater sediment, the results of this test – combined with sediment toxicity results with invertebrates – were deemed to be a sensitive indicator of sediment porewater toxicity (Keddy et al. 1995).

All appropriate and required quality assurance and quality control measures were employed for the above-mentioned tests conducted during both years (see Supplementary Materials for additional details).

To determine if the effect measured in the toxicity testing would negatively impact the representative population, the effect size was calculated. This calculation integrated

the effects measured in the control samples (i.e., lab control and site reference) and the effects measured in the corresponding test sample(s) in the following equation:

$$\text{Effect size} = \frac{(\text{control sample} - \text{test sample})}{\text{control sample}}$$

### Bioaccumulation potential testing and evaluation

As indicated above, the 28-day *Lumbriculus variegatus* (freshwater mudworm) survival and bioaccumulation test (US EPA 2000) was used to evaluate both toxicity and sediment biota bioaccumulation potential. The bioaccumulation potential of PAHs was predicted from the measured concentrations of PAHs in the *L. variegatus* tissue and the corresponding sediment sample.

The resulting Biota Sediment Accumulation Factor (BSAF) is calculated according to Ankley et al. (1992), as follows:

$$\text{BSAF} = \frac{(C_t/f_l)}{(C_s/f_{\text{soc}})}$$

where  $C_t$  is the concentration in the tissue,  $f_l$  is the lipid fraction in the tissue (g lipid/g wet weight),  $C_s$  is the concentration in sediment,  $f_{\text{soc}}$  is the organic carbon fraction in sediment (g organic carbon/g dry weight).

The accumulated tissue concentrations were compared to literature-based toxicity reference values (TRVs). These critical body residue (CBR) TRVs represent the accumulated concentration in tissue that results in a toxic effect in 20% or less of the test organisms. Using these TRVs, a hazard quotient (HQ) is calculated using the following equation:

$$\text{HQ} = \frac{C_t}{\text{TRV}}$$

If the resulting HQ is greater than one, then the potential for adverse impacts is predicted.

### Coal analysis

In 2014, a sample of metallurgical coal from Teck Coal's Line Creek Operations (Elkford, BC; the location from which the coal originated) was submitted to Maxxam

Analytics (Burnaby, BC) to determine chemical composition. The results, in conjunction with information provided in the Teck Material Safety Data Sheet (MSDS), were used to characterize the coal spilled into Silver Creek. The results of this analysis were not included in the LOE assessment but were used for illustrative purposes.

### Coal particle content

In 2015, selected sediment samples (i.e., from stations S15-01, S15-03, S15-04, S15-05, S15-07 and S15-08) were shipped to the Acuren Group Inc. (Richmond, BC, Canada) for analyses of the coal content. Samples were first dried at 110 °C, then sieved through 0.8 mm, 0.2 mm and 10 µm sieves and weighed. From these sieved fractions, the estimated coal content was evaluated using a Hitachi SU-3500 scanning electron microscope (SEM) interfaced with an energy-dispersive X-ray analysis (EDXA) system. Representative SEM specimens from each sieved fraction were examined at low and high magnifications. Particles were visually examined for surface appearance, angular features and composition using the EDXA system. The number of coal particles by size class was counted to calculate a percentage of coal present within sediment samples for each particle size class (i.e., >0.8 mm, 0.8 to >0.2 mm and 0.2 mm to >10 µm).

### WOE approach using integrated LOEs

A WOE approach integrated multiple LOEs, including: sediment quality, sediment toxicity, bioaccumulation potential of constituents of concern in the sediment and coal particle content analysis. A summary of the analyses conducted at the sampling stations is presented in Table 1.

**Sediment Chemistry.** Constituent concentrations in sediment exceeding the CCME PEL or the BC MOE Upper SWQG are an indication that effects are likely to occur frequently to biota due to constituents of concern in the sediment. The CCME ISQG and the BC MOE Lower SWQG are criteria that will protect biota in the sediment from adverse effects in most situations; exceeding these criteria may result in adverse effects, while concentrations of constituents in the sediment that are less than these criteria are unlikely to result in adverse impacts.

**Table 1** | Analyses of the LOEs at sampling locations in Silver Creek and Burnaby Lake (2014–2015)

| Sample ID | LOE       |          |                           | Coal |
|-----------|-----------|----------|---------------------------|------|
|           | Chemistry | Toxicity | Bioaccumulation potential |      |
| S14-01    | ✓         | ✓        | ✓                         | X    |
| S15-01    | ✓         | ✓        | ✓                         | ✓    |
| S15-02    | ✓         | X        | X                         | X    |
| S14-03    | ✓         | ✓        | ✓                         | X    |
| S15-03    | ✓         | ✓        | ✓                         | ✓    |
| S15-04    | ✓         | X        | X                         | ✓    |
| S15-05    | ✓         | ✓        | ✓                         | ✓    |
| S15-06    | ✓         | X        | X                         | X    |
| S15-07    | ✓         | ✓        | ✓                         | ✓    |
| S15-08    | ✓         | ✓        | ✓                         | ✓    |
| S14-09    | ✓         | ✓        | ✓                         | X    |
| S14-10    | ✓         | ✓        | ✓                         | X    |
| S14-11    | ✓         | X        | X                         | X    |
| S14-12    | ✓         | ✓        | ✓                         | X    |
| S14-13    | ✓         | X        | X                         | X    |

The ✓ indicates locations where samples were collected and analysis conducted; conversely, X indicates that analysis did not occur at this location for this parameter.

**Sediment/Leachate/Porewater Toxicity.** To test the hypothesis that sediment has the potential to cause adverse effects to resident sediment organisms, unacceptable impacts to the aquatic population were predicted if the toxicity effect threshold of 20% was exceeded (i.e., 20% or more of the population impacted or EC20). Exceeding a toxicity threshold of 50% effect (i.e., LC50 or EC50) indicates that greater than 50% of the organisms tested were adversely affected, which, when extrapolated to the population level, could result in impacts to over half of the organisms living in the water body. Using these benchmarks as a ranking system is in agreement with the framework presented in Chapman et al. (2002).

**Bioaccumulation Potential.** Bioaccumulation potential represents the uptake of constituents of concern from the environment from all media, via both passive transfer and dietary uptake. A BSAF of 1.7 is the threshold of accumulation reflective of bioaccumulation potential (McFarland & Clarke 1986; Ingersoll & McDonald 2003). In other words, when the concentration of the constituent in the

organism's body is 1.7 times that of the media of concern (in this case, sediment), that constituent is said to have bioaccumulation potential. Bioaccumulation itself may not be a reason for concern, unless the accumulated concentrations exceed CBR TRVs, then those accumulated concentrations could cause adverse effects.

**Coal Particle Content Analysis.** Given that provincial or federal standards do not exist for coal concentrations in sediment that could be hazardous to ecological health, an *a priori* framework was developed based on the recommendation of McDonald et al. (2007). Since the uptake of coal into biota is contingent on particle size (Talley et al. 2002; Ahrens & Morrisey 2005), a higher relative proportion of the smallest fraction of coal measured (i.e., 0.2 mm to >10 µm) was considered more hazardous. Hence, a sample containing greater than two-thirds of coal in the 0.2 mm to >10 µm fraction was ranked as having a high potential for hazard; a

sample containing between one- and two-thirds in the 0.2 mm to >10 µm fraction was ranked as moderate and a sample containing one-third in the 0.2 mm to >10 µm fraction or lower was ranked as low. The trend presented in the coal concentrations sheds light on the potential link between contaminant concentrations in coal and ecological impacts.

The results of each LOE at each station are ranked according to Table 2, then integrated using the presented matrix to evaluate the potential for adverse impacts to Silver Creek and Burnaby Lake sediment biota.

The WOE framework using integrated LOEs was also determined *a priori*. To determine the weight to be applied to each LOE, best professional judgement was applied. The criteria used to determine the weight applied to each LOE included: strength of association, sensitivity and specificity, data quality and study design, representativeness, and correlation/causation/consistency (Menzie et al. 1996;

**Table 2** | Ranking system for integrative LOEs (adapted from Chapman et al. (2002))

| LOE [Weight]  | ● – High   | ◎ – Moderate  | ○ – Low  |
|---|--|---|--|
| Sediment chemistry [0.75]                                 | Exceedance of CCME PEL or the BC Upper SWQG*   | Exceedance of either CCME ISQG, BC Lower SWQG or Approved WQG (Sediment) Criteria for Aquatic Life*           | Less than sediment quality guidelines  |
| Sediment toxicity ( <i>C. dilutus</i> ) [1]               | Toxic effect is 50% or greater (i.e., ≥ LC50 or EC50)  | Toxic effect is 20% or greater (i.e., ≥ LC20 or EC20)   | Toxic effect is less than 20% (i.e., < LC20 or EC20)   |
| Sediment toxicity ( <i>H. azteca</i> ) [1]                | Toxic effect is 50% or greater (i.e., ≥ LC50 or EC50)  | Toxic effect is 20% or greater (i.e., ≥ LC20 or EC20)   | Toxic effect is less than 20% (i.e., < LC20 or EC20)   |
| Sediment leachate toxicity ( <i>O. mykiss</i> ) [1]       | Toxic effect is 50% or greater (i.e., ≥ LC50 or EC50)  | Toxic effect is 20% or greater (i.e., ≥ LC20 or EC20)   | Toxic effect is less than 20% (i.e., < LC20 or EC20)   |
| Sediment porewater toxicity ( <i>P. subcapitata</i> ) [1] | Toxic effect is 50% or greater (i.e., ≥ LC50 or EC50)  | Toxic effect is 20% or greater (i.e., ≥ LC20 or EC20)   | Toxic effect is less than 20% (i.e., < LC20 or EC20)   |
| Bioaccumulation potential ( <i>L. variegatus</i> ) [1]    | Bioaccumulation factor (BSAF) is greater than 1.7, and the tissue body burden exceeds the critical body residue (i.e., HQ > 1) | BSAF is greater than 1.7, but the tissue body burden does not exceed the critical body residue (i.e., HQ < 1) | BSAF is less than 1.7, and the tissue body burden does not exceed the critical body residue  |
| Coal content [0.5]  | Proportion of coal that is 0.2 mm to >10 µm in size is greater than two-thirds of the total coal                               | Proportion of coal that is 0.2 mm to >10 µm in size is between 33% and 66% of the maximum concentration       | Proportion of coal that is 0.2 mm to >10 µm in size is less than one-third of the total coal |
| Overall potential for impact                              | High – Significant detrimental impacts predicted   | Moderate – Impacts possible but smaller in magnitude  | Low – Significant detrimental impacts are not predicted                                      |

Those LOE with ranked ● indicate a high ranking, whereas those LOE with a ◎ rank have a moderate ranking, and a low ranking is indicated by ○.

Note: \* indicates that a single exceedance of any constituent is sufficient to determine the category for that sample.



**Table 3** | LOE weighting and scoring system in the WOE assessment

| LOE   | LOE weight | LOE score   |                  |              |
|---|------------|-------------|------------------|--------------|
|   |            | ○ = 1 (Low) | ⊙ = 2 (Moderate) | ● = 3 (High) |
| Sediment chemistry                                    | 0.75       | 0.75        | 1.5              | 2.25         |
| Sediment toxicity ( <i>C. dilutus</i> )               | 1          | 1           | 2                | 3            |
| Sediment toxicity ( <i>H. azteca</i> )                | 1          | 1           | 2                | 3            |
| Sediment leachate toxicity ( <i>O. mykiss</i> )       | 1          | 1           | 2                | 3            |
| Sediment porewater toxicity ( <i>P. subcapitata</i> ) | 1          | 1           | 2                | 3            |
| Bioaccumulation potential                             | 1          | 1           | 2                | 3            |
| Coal content  | 0.5        | 0.5         | 1                | 1.5          |

In order to transparently and quantitatively summarize the lines of evidence into a weight-of-evidence assessment, the ranking framework was converted into a cardinal, numerical system. Each rank was assigned a value, where ○ = 1, ⊙ = 2, ● = 3. This value was multiplied by the weight of the LOE to get a score.

(SABCS 2010). Among the five LOEs, equal weighting is not applied, as some LOEs present higher values than others (Table 3). Based on recommended weighting in guidance (Menzie et al. 1996; SABCS 2010), sediment toxicity and bioaccumulation potential are all weighted with an LOE score of 1. Sediment chemistry is weighted as 0.75, as there is less of a connection with biological/ecological response, in comparison with sediment toxicity and bioaccumulation potential. The relevance of the coal particle content to the biological process has not been well detailed in the literature, and the link between concentrations measured and effects are unclear; hence, this LOE is scored as 0.5. For each sampling station, the weighted ranks of all LOEs are summed, and the potential for impacts based on the LOE score is determined based on Table 4.

**Table 4** | *A priori* ranking for WOE assessment

| Average LOE score | Overall potential for impact |
|-------------------|------------------------------|
| 0.9 to 1.5        | ○ – Low                      |
| >1.5 to 2.1       | ⊙ – Moderate                 |
| >2.1 to 2.7       | ● – High                     |

Note: The total value for each sampling location was summed and then divided by the number of LOEs evaluated for that location to get an average LOE score.

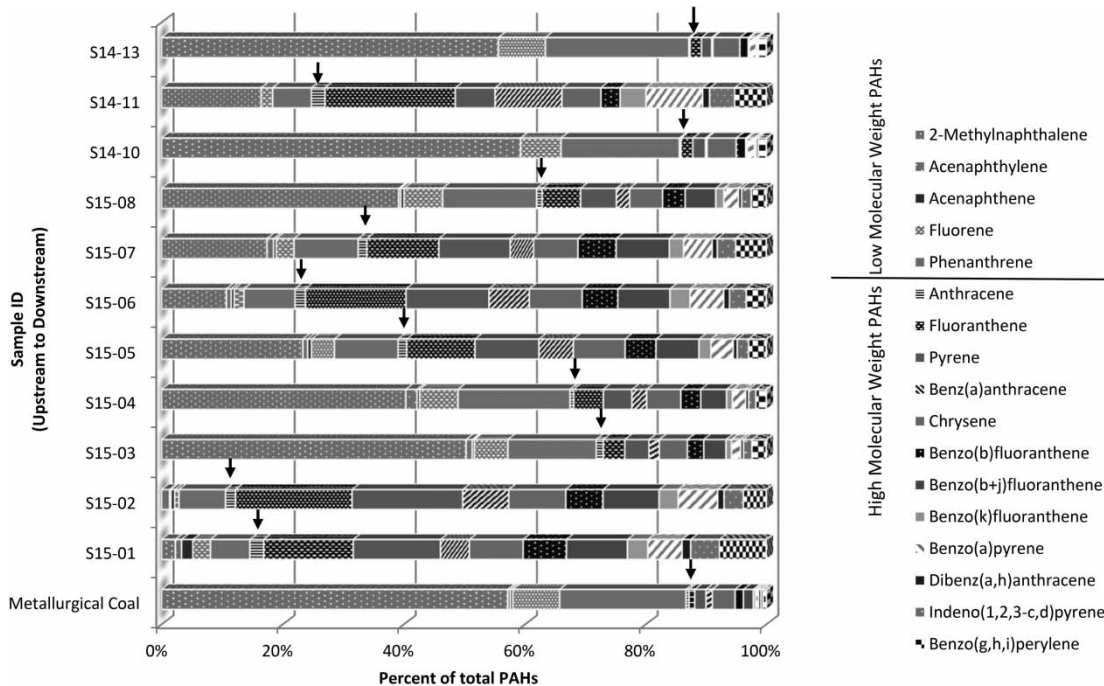
## RESULTS AND DISCUSSION

### Sediment quality

In 2014, for sediments collected from Silver Creek and Burnaby Lake, the only exceedances of sediment quality guidelines for metals were cadmium, copper and nickel, and these occurred only at station S14-09 (the Burnaby Lake reference station; not exposed to the spilled coal). Since metallurgical coal generally does not contain elevated concentrations of metals, these elevated concentrations are likely either natural or originated from a source other than the coal spill. In 2015, a single station (i.e., S15-02, not sampled in 2014) yielded arsenic concentrations in excess of CCME ISQG/BC MOE Lower SWQG. Individual PAHs exceeded guidelines at multiple stations in both 2014 and 2015. It is important to note that reference stations (i.e., S14/S15-01) did not yield PAH concentrations in excess of applicable guidelines. A summary of the sediment exceedances and their stations for both 2014 and 2015 are presented in Supplementary Table S-1.

In the interest of comparing the PAH profiles in the sediment to the metallurgical coal spilled during the derailment, a sample of coal was analyzed at Maxxam Analytics. The metallurgical coal yielded elevated concentrations of certain low-molecular weight (LMW) PAHs, specifically: naphthalene, 2-methylnaphthalene, fluorene and phenanthrene, but concentrations of other LMW PAHs (i.e., acenaphthylene, acenaphthene and anthracene) were below method detection limits (MDLs). Concentrations of high-molecular weight (HMW) PAHs were not as elevated as LMW PAHs. Hence, the ‘fingerprint’ of PAHs derived from coal in sediment would be predicted to be an elevated suite of LMW PAHs and detectable concentrations of HMW PAHs (Figure 3).

Given the increased likelihood of mechanical and metabolic breakdown for LMW PAHs over time, these constituents may not persist as a stable fingerprint due to degradation. While the sediment chemistry from the initial samples collected in 2014, within 5–6 months post-spill, show a similar pattern in high concentrations of LMW PAHs and detections of HMW PAHs, the samples collected in 2015 do not as closely resemble this pattern, potentially due to the removal of the majority of the source coal and weathering of the residual PAHs.



**Figure 3** | PAH profiles of Silver Creek sediments compared to metallurgical coal. The 'fingerprint' of PAHs derived from coal in sediment is indicated by an elevated suite of low-molecular weight (LMW) PAHs and detectable concentrations of high-molecular weight (HMW) PAHs. Arrows indicate the division between LMW PAHs and HMW PAHs.

### Sediment/leachate/porewater toxicity testing and bioaccumulation potential

The results of the toxicity testing were species- and endpoint-specific (see Supplementary Tables S-2 to S-10 and S15). For tests conducted exclusively in 2014 (i.e., rainbow trout survival and *P. subcapitata*), no impacts to either survival or growth of these species were noted based on the testing. Significant impacts (i.e., greater than an effect size of 20%, relative to lab control and/or field reference) were noted in 2014 for chironomid and *Hyallolella* survival when exposed to sediments from station S14-03. As well, bioaccumulation potential of total PAHs from sediments collected at station S14-03 into *L. variegatus* was also noted. However, these accumulated concentrations were not sufficient to result in the prediction of risks to *L. variegatus*. For sediment samples collected in 2015, no effects to chironomids or *Hyallolella* were measured, and PAHs concentrations in *L. variegatus* did not indicate bioaccumulation potential.

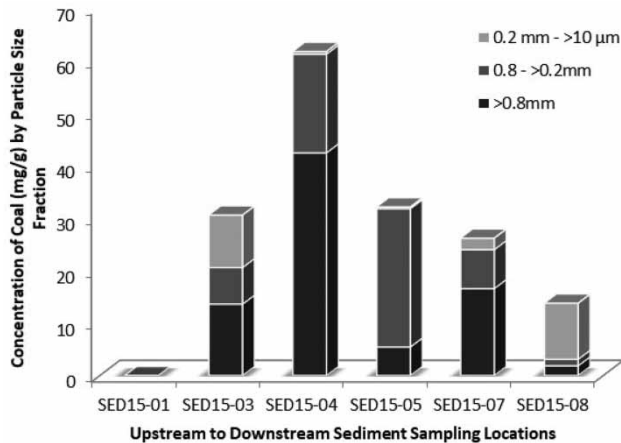
Only one exposure station identified in 2014 was re-sampled in 2015 (i.e., station S14/S15-03). Toxicity of sediments to chironomid and *H. azteca* toxicity testing at this

location decreased from 2014 to 2015 (see Supplementary Tables); in 2014, survival in both chironomids and *H. azteca* was significantly impacted (i.e., 70% and 76% of the control survival, respectively), whereas in 2015, survival was 94% and the same or better than the control group.

Bioaccumulation potential testing was conducted in both 2014 and 2015 at station S14/S15-03. Total PAHs were found to be bioaccumulating in *L. variegatus* with a BSAF of 2.23; in 2015, the potential for bioaccumulation of total PAHs was decreased, as the resulting BSAF was 0.07 (see Supplementary Tables S-11 to S-14 and S16). This trend is reflective of the general decline trend in sediment PAH concentrations in Silver Creek.

### Coal particle content analysis

In the 2015 samples, coal content analysis indicated that coal was not present in the upstream station (i.e., S15-01), peaked in concentration at the bend of Silver Creek (i.e., S15-04) and declined in concentration towards the Brunette River. At the confluence of Silver Creek and Burnaby Lake (i.e., S15-08), the concentrations of coal constituents were



**Figure 4** | Coal concentrations trend – upstream to downstream. Coarse (>0.8 mm) deposits of coal are indicated by the dark sections of the bar, the medium gray indicates the concentration of coal deposits between 0.8 and 0.2 mm in diameters and the light gray reflects the fine coal particulate (0.2 mm to >10 μm) concentration.

still measurable. Figure 4 illustrates the concentrations of coal constituents present at the six sampling stations, as well as the proportion of the measured coal that had fine, medium or coarse particle size.

As a general trend, the amount of coal associated with the smallest particle size fraction (i.e., 0.2 mm to >10 μm) increased downstream from station S15-04 towards S15-08. These results likely reflect the transport of the coal particles from the source down Silver Creek. These finer particles are more bioaccessible to biota, and potentially present a greater potential for impact. Station S15-03 also had a higher accumulation of coal fines present as compared to other sites, potentially due to hydrodynamics (the sharp bend in Silver Creek at this station) resulting in increased deposition.

### LOE analysis

The results of the LOE analysis for each sampling station from 2014 and 2015 are presented in Table 5. At the upstream reference stations (i.e., stations S14-01 and S15-01), the sediment chemistry, toxicity and bioaccumulation potential were low, and coal was not detected, so significant adverse impacts are not expected. There were sediment quality guideline exceedances at station S14-03, and moderate toxicity effects to chironomids and *H. azteca*, as well as

bioaccumulation potential of PAHs to *L. variegatus*, but low toxicity of sediment leachate/porewater, so the overall WOE rank at this sampling location is moderate. Given the results of the testing at this station in 2014, this location was reassessed in 2015 (assessed as S15-03), and the likelihood for detrimental impacts was cumulatively determined to be low. At station S15-03, the potential for impacts due to toxicity or bioaccumulation is low, but there is moderate potential for impacts due to chemistry and coal content. Similarly, at S15-05 and S15-07, the potential for impacts due to toxicity and bioaccumulation is low, there is moderate potential for impacts due to chemistry; however, the potential for impacts due to the coal content is low. Overall, the likelihood of impacts is low, and significant adverse impacts are not predicted. At stations S15-08 and S14-10, there were sediment quality guideline exceedances and a greater proportion of the smallest coal fraction (S15-08 only) but low toxicity and bioaccumulation potential. Hence, the WOE score indicates that significant adverse effects are not predicted. At stations S14-09 and S14-12, sediment chemistry and coal content were not collected, but the full suite of toxicity tests was conducted. As the results of these tests showed a low potential for impact, the overall likelihood for impacts, based on the WOE score, were determined to be low.

For those sampling stations at which less than a full suite of tests was conducted (i.e., stations S15-02, S15-04, S15-06, S14-11 and S14-13), correlations in sediment chemistry between these stations and stations for which there were toxicity testing data were made to determine that station's potential for impact. For stations S15-02 and S15-06, given that the concentrations of coal-associated constituents in sediments are in the same range as at stations S15-03 and S15-05, similar results in bioaccumulation potential and toxicity testing would be expected. Therefore, the likelihood of adverse impacts is determined to be low. For station S15-04, the coal content was the highest of all the stations (although the proportion of the smallest coal fraction was low), and there were PAH exceedances of the sediment quality guidelines for 2-methylnaphthalene (i.e., high potential for impact), so there is a high potential for adverse impacts at this station. Note that this assessment was conducted after additional remediation conducted at this station. Comparison of chemistry results at stations S14-11 and S14-13 to

**Table 5** | Assessment of low, moderate or high potential for impact based on LOEs

| LOE   | Weight | S14-01 | S15-01 | S15-02 | S14-03 | S15-03 | S15-04 | S15-05 | S15-06 | S15-07 | S15-08 | S14-09 | S14-10 | S14-11 | S14-12 | S14-13 |
|---|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Sediment chemistry                                    | 0.75   | ○      | ○      | ⊙      | ●      | ⊙      | ●      | ⊙      | ⊙      | ⊙      | ●      | -      | ●      | ●      | -      | ●      |
| Sediment toxicity chironomids                         | 1      | ○      | ○      | -      | ⊙      | ○      | -      | ○      | -      | ○      | ○      | ○      | ○      | -      | ○      | -      |
| Sediment toxicity <i>Hyallolella</i>                  | 1      | ○      | ○      | -      | ⊙      | ○      | -      | ○      | -      | ○      | ○      | ○      | ○      | -      | ○      | -      |
| Sediment leachate toxicity <i>O. mykiss</i>           | 1      | ○      | -      | -      | ○      | -      | -      | -      | -      | -      | -      | ○      | ○      | -      | ○      | -      |
| Sediment porewater toxicity ( <i>P. subcapitata</i> ) | 1      | ○      | -      | -      | ○      | -      | -      | -      | -      | -      | -      | ○      | ○      | -      | ○      | -      |
| Bioaccumulation                                       | 1      | ○      | ○      | -      | ⊙      | ○      | -      | ○      | -      | ○      | ○      | ○      | ○      | -      | ○      | -      |
| Coal content  | 0.5    | -      | ○      | -      | -      | ⊙      | ○      | ○      | -      | ○      | ●      | -      | -      | -      | -      | -      |
| Overall potential for impact*                         |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Score   |        | 1.0    | 0.9    | **     | 1.7    | 1.1    | **     | 1.0    | **     | 1.0    | 1.4    | 1.0    | 1.2    | **     | 1.0    | **     |
| Rank  |        | ○      | ○      | **     | ⊙      | ○      | **     | ○      | **     | ○      | ○      | ○      | ○      | **     | ○      | **     |
| Final conclusion for the potential for impact         |        | ○      | ○      | ○      | ⊙      | ○      | ●      | ○      | ○      | ○      | ○      | ○      | ○      | ●      | ○      | ●      |

Note that ○ = Low: Significant detrimental impacts are not predicted; ⊙ = Moderate: Impacts possible, but smaller in magnitude; ● = High: Significant detrimental impacts predicted; - LOE not conducted for this location. For those LOE where the score and rank is indicated as \*\*, only one or two LOE were assessed, so a chemistry-toxicity correlation was extrapolated to determine potential for impacts.

S14-10, where a full suite of toxicity testing was conducted, was conducted to interpolate the potential for impact at these stations. Station S14-13 yielded concentrations of HMW PAHs equivalent to station S14-10, and concentrations of LMW PAHs were similar, so it was extrapolated that the potential for coal spill-related impacts at this station was low. However, at station S14-11, concentrations of HMW PAHs were greater but had lower concentrations of LMW PAHs and had more constituents which exceeded sediment quality guidelines, as compared to those at station S14-10. While the pattern of PAHs present does not match the coal fingerprint (which is proportionally high concentrations of LMW PAHs relative to HMW PAHs), concentrations at station S14-11 are such that interpolation with nearby sediment samples is not feasible. Hence, the potential for impact at this location remains high, with a significant degree of uncertainty.

## CONCLUSION

In this AIA, the potential impacts of residual coal were evaluated post-completion of spill recovery efforts subsequent to the derailment. Following the derailment and subsequent spill, a precautionary risk management approach was used, in which the majority (more than 90%) of the volume of the coal was removed from the spill site. This remediation approach was deemed the preferred option, given the urgency expressed by regulatory agencies and the general public, rather than the longer process alternative (i.e., risk assessment approach), which would first assess the potential biological impact of the spill and consider whether or not clean up was necessary, and if so, to what extent. However, a balance was required, such that the ecological costs of the remediation did not exceed the benefits of coal removal. With this in mind, a residual amount of coal was left *in situ*, as complete excavation would have required extensive excavation, and possibly impacted the habitat and flow of Silver Creek.

This AIA utilized a WOE approach to evaluate the potential impacts from the coal remaining from the spill to the aquatic receiving environments of Silver Creek and Burnaby Lake. Based on the results of the WOE, it was determined that further monitoring was not required. The

majority of the sampling stations indicated that there was a low potential for impact, based on the assessed LOEs. At the stations where the potential for impact was assessed to be moderate or high, it was decided that natural attenuation and sedimentary degradation would effectively eliminate any biotic exposure to the residual coal deposits. The stations at which the potential for impact was predicted were localized; stations S14-03 and S15-04 were clustered at the bend of Silver Creek on a depositional bar and stations S14-11 and S14-13 were downstream within Burnaby Lake. Given the overall low potential for impacts remaining due to coal deposits in the Silver Creek–Burnaby Lake ecosystem, no further monitoring was conducted.

## SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at <https://dx.doi.org/10.2166/wqrj.2020.018>.

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