Sediment Impact to GVW Kalamalka Lake Intake Study, 2018

Prepared for
Regional District of North Okanagan

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Executive Summary

This study was designed to answer questions involving the sediment accumulation rate, sediment contaminants and their sources in the North Arm of Kalamalka Lake, and to identify the risk posed by these materials to drinking water quality at the RDNO intake. Sediments act as a reservoir for contaminants and can return them to the water column during turbulent re-suspension.

Coarse sediment accumulated near the mouth of Coldstream Creek, while silts deposited farther along the plume path, and clays were transported throughout the North Arm. Sediments near the creek contained less marl than the very fine marl-based lake sediments that dominate elsewhere in the Arm. Despite high *E. coli* counts in Coldstream Creek flows, this study found low sediment *E. coli* concentrations at sites within its plume path. The highest sediment *E. coli* counts occurred at sites adjacent to stormwater outfalls and at deep sampling sites. Fecal bacteria contamination of sediment from traps deployed near the intake location is concerning. Seagulls congregating near the intake buoy (deep sites) as well as turbulent transfer of contaminated sediments from shallows near stormwater outfalls to the intake area are the likely causes.

Sediment traps deployed from spring through fall 2018 collected recently deposited or disturbed sediments. This sediment demonstrated a pattern of higher heavy metal concentrations along the Coldstream Creek plume path than at other North Arm sites. Like most lakes within urban watersheds, sites with sediment metal exceedances were also affected by stormwater or a marina. Chromium, copper, iron, and nickel exceeded their respective sediment guidelines in the sediment trapped during the 2018 boating season, indicating ongoing metal loading to Kalamalka Lake. Viable fecal bacterial caught in the sediment traps demonstrated that bacteria contamination is an ongoing issue in the North Arm. Sediment contaminants are a cause for concern when shallow sediments become re-suspended by turbulence.

Distributions of numerous metals in core samples also exhibited a pattern indicative of Coldstream Creek silts as a key source of sediment metals. Samples from deep sediment layers deposited decades ago had similar metal distributions, indicating that Coldstream Creek has been a source of sediment metals for decades. Nickel slightly exceeded the BC MoE sediment guidelines in silty sediment cores from sites flanking the main plume that also receive turbid flows from stormwater outfalls or from the marina. Nickel is a common contaminant in stormwater and at marinas. These localized metal sources are important, but Coldstream Creek remains the main source of sediment and sediment metals into the North Arm of Kalamalka Lake because it receives agricultural and transportation runoff in its upper reaches as well as urban stormwater in its lower reaches.

Sediments with hydrocarbon contamination and elevated metal concentrations were detected about 100 m offshore from stormwater outfalls (Core Site 3). Several hazardous PAHs associated with urban stormwater exceeded their respective CCME sediment guidelines for protection of aquatic life at that site. Based on hydrocarbon fingerprinting, the likely source of these PAHs is stormwater from a series of nearby stormwater outfalls, though intensive power boating that occurs near Core Site 3 may also contribute to these sediment PAH exceedances. A companion study in 2016 found PAH exceedances at two marinas and the Oyama Canal, indicating power boating impacts and hydrocarbon contamination of the fine clayey substrate that collects within marinas. Both sediment studies did not find hydrocarbon contamination in sediments collected offshore from the Kalavista Boat Launch; these results are likely due to the low retention of hydrocarbons in

coarse/sand gravel substrates near the creek mouth. Regardless of the original PAH source, boat wake and wave re-suspension of these persistent and toxic sediment contaminants is a concern.

This study established the presence of three categories of contaminants in North Arm Kalamalka Lake sediments: metals, PAHs, and fecal bacteria. As in many lakes, the North Arm sediments act as a reservoir for these contaminants. Activities that disturb large areas of fine sediment such as rototilling or wakeboard/wakesurf boats in water shallower than 4-5m will generate a turbidity plume that can redistribute sediment contaminants to deeper water. These activities cause episodes of high turbidity that adversely impact water treatment (Schleppe et al, 2017). Some of the high sediment accumulation measured in the deep sediment traps near the RDNO intake likely originated from the shallows and are not entirely the result of whole-lake phenomena such as marl precipitation and settling of algae cells.

The upgraded RDNO North Kalamalka Lake intake has 3.5 m of clearance from the lake bottom (20 m depth from surface). Compared to the preceding intake with 0.6 m of clearance, the upgrade improved protection from re-suspended sediment contaminants and resulted in lower turbidity. Shallow private intakes in the North Arm do not enjoy the protection from sediment-borne contaminants that the RDNO intake does.

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Preferred Citation:
J. Self and Larratt, H., 2019. Kalamalka Lake North Arm 2018 Sediment Study. Prepared by Larratt Aquatic Consulting Ltd. Prepared for Regional District of North Okanagan.

1.0 Study Overview

Kalamalka Lake is the second largest of the Okanagan Valley mainstem lakes. It is very popular for summer recreation including powerboating, stand-up paddle-boarding, kayaking, and swimming. Kalamalka Lake is also a major source of drinking water for the City of Vernon, District of Coldstream, RDNO electoral areas B&C and District of Lake Country.

Kalamalka Lake is a marl lake. Each summer, conditions become favorable for the formation of calcium carbonate (calcite = $CaCO_3$) and calcium sulphate (gypsum = $CaSO_4 \cdot 2(H_2O)$) crystals that together form marl. Marl crystals reflect light and give the lake its famous teal coloring (Figure 1-1). Marl crystals take weeks to settle out of the water column before accumulating on the lake bottom. The marl sediment of Kalamalka Lake is very fine-grained and is readily re-suspended (Larratt and Self, 2017; Schleppe et al., 2017).

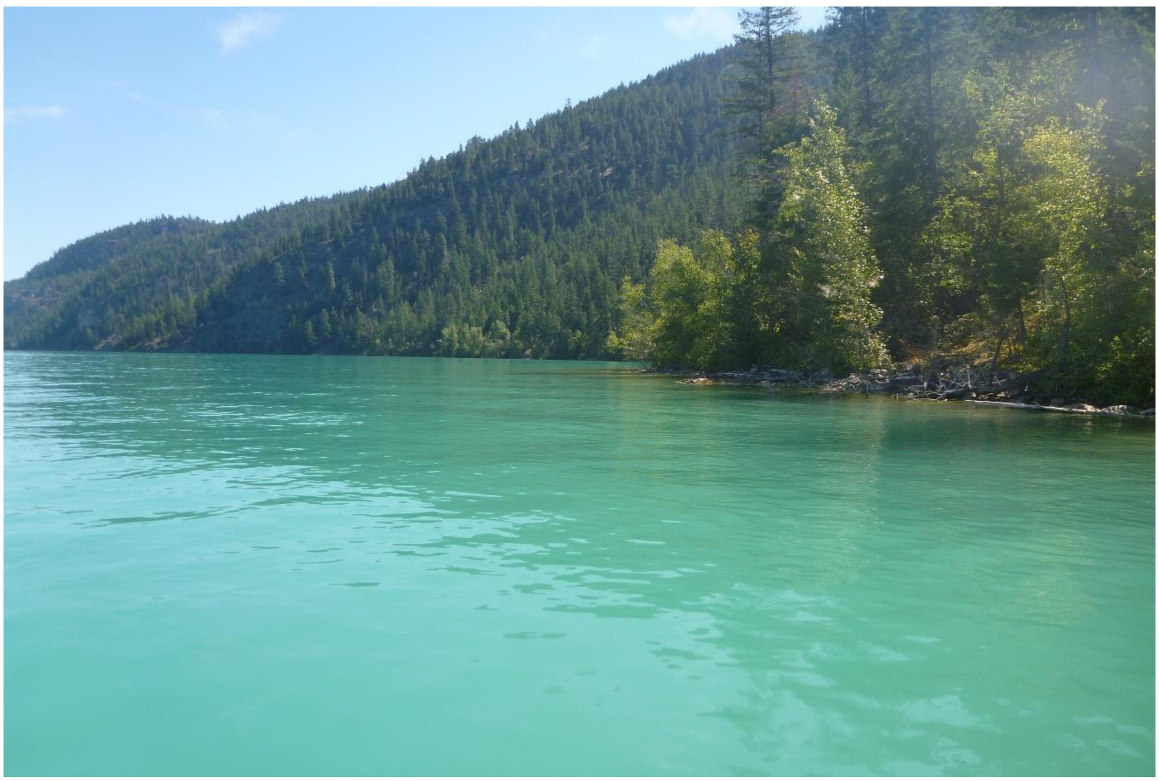

Figure 1-1: Kalamalka Lake during marl event

Coldstream Creek is the main tributary into Kalamalka Lake and flows into the North Arm. Mapping of the creek's plume shows that it splits, with the concentrated plume heading south in the middle of the Arm, and another portion flowing north along the shoreline (Figure 1-2). During the high freshet years of 2017 and 2018, the Coldstream Creek channel transported unusually high sediment loads. In all freshets, the coarser sand and gravel component dropped out quickly and built the fan at the creek mouth and lower channel. The finer silts deposit along the creek plume path, while the clays are transported throughout the North Arm by annual freshet flows.

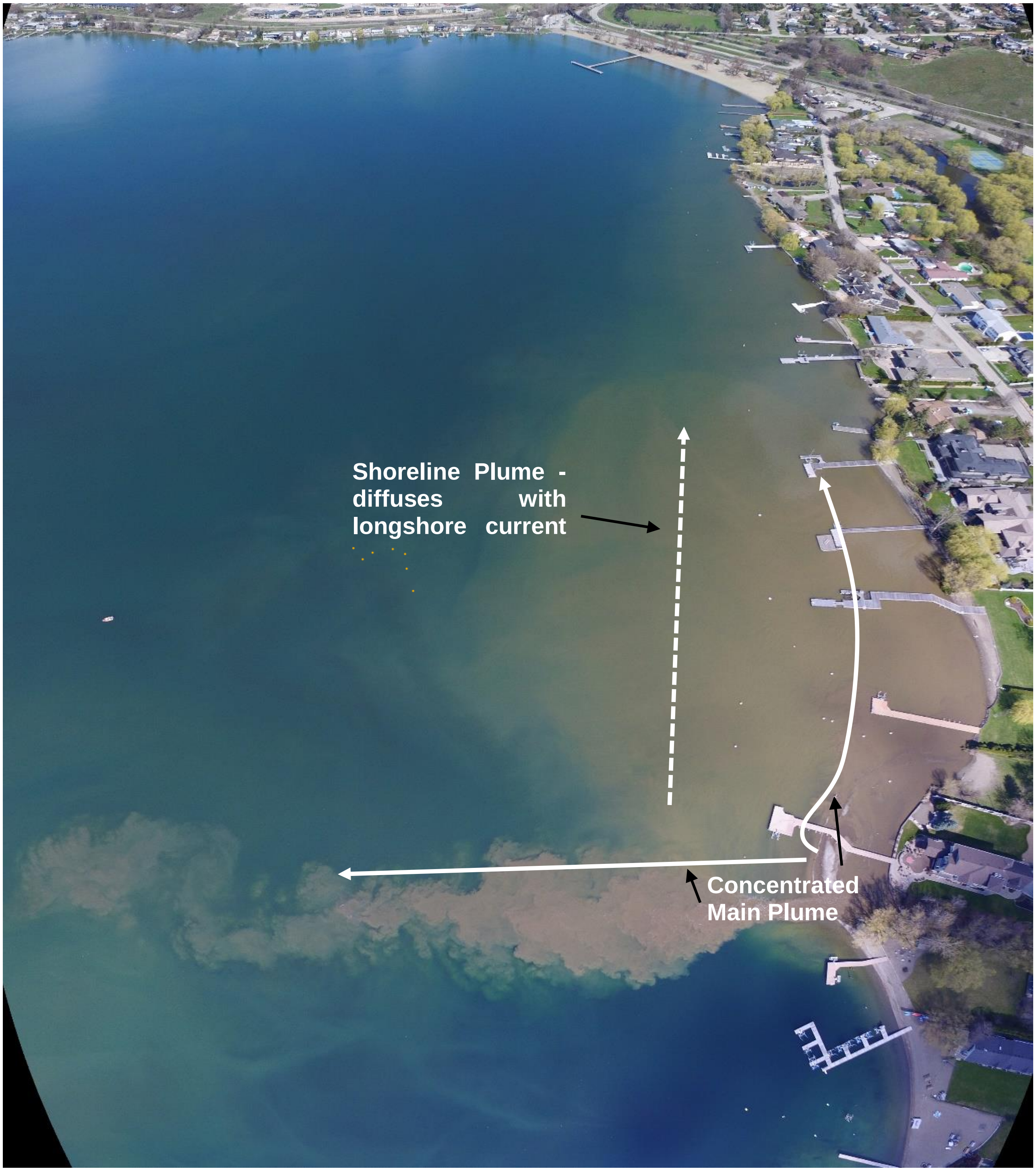

Figure 1-2: Aerial photo of Coldstream Creek plume during early freshet on April 22, 2017

Note: Majority of plume travelled straight out into the lake towards the 30 m sampling site. Longshore currents travel south (bottom) to north (top) in this location and diffused the plume northwards along the shore. By May, the entire North Arm was turbid.

Lake sediments are the final repository of natural and anthropogenic contaminants produced or derived in their watersheds. Many toxic and bioaccumulative chemicals such as metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), chlorophenols, and organochlorine pesticides that are found in only trace amounts in water, can accumulate to elevated levels in sediments (MacDonald and Ingersol, 2001).

Locating contaminated sediments is necessary because they can be a secondary source of pollution when they become re-suspended within a water body (Forstner and Heise 2006). The 2016 Kalamalka Lake boating capacity study identified sediment re-suspension by powerboating as a potential risk to drinking water intakes (Schleppe et al., 2017). Given the sediment contaminant re-suspension risk, this study was designed to answer the following questions:

- What is the sediment accumulation rate in the North Arm of Kalamalka Lake?
- What contaminants were present in sediment that accumulated in 2018?
- What is the status of possible hazardous contaminants already accumulated in the sediment?
- What are the likely sources of present and past contaminants within Kalamalka Lake sediment?
- What is the risk to drinking water presented by sediment contaminants?

This study set out to answer these questions through two types of sediment sampling, with a focus on shallow areas that are more likely to be disturbed. The first was to take sediment cores at several sites around the perimeter of the North Arm and analyze the sediments for metals, hydrocarbons, and fecal bacteria. The second approach was to install sediment traps around the perimeter of the North Arm to measure sediment accumulation rates during summer 2018. The collected sediment was also analyzed for metals and bacteria.

Marina substrates were not re-sampled as part of this study. PAH and metals contamination of these sediments was identified in the Kalamalka Boating Study (Schleppe et al. 2017) and confirmed by literature review. PAH contamination of these sediments is inevitable. We also did not sample sediments immediately in front of stormwater outfalls where again, PAH, metals, and *E. coli* contamination is demonstrated and inevitable (Summit 2012; Kerr Wood Leidel 2017). These localized contaminated sediments are concerning, but this study is focused on generalized sediment contamination with the potential to reach the water treatment intake. We therefore sampled sediments in 4 – 25 m depth of water and about 50 - 100 m from shore to assess the risk posed by migration of sediment contaminants from known shoreline sources.

2.0 Methods

2.1 Sediment Core Collection

Sediment coring provides a history of these watershed pollutants and the depth to which contamination extends. Sediment cores were collected by remote corer at five North Arm sites and at one site within Coldstream Creek in 2018. Three replicate cores were collected at each site and separated into layers. The replicate layers were combined into the sediment sample jar and chilled (Bloesch. 1994). The sites were distributed from 40 to 125 100 m offshore focusing on areas of high potential impact (Figure 3-1; Table 2-1). Core Site 1 was 85 m from the private 12 berth Kidstron Road marina and Core Site 2 was 90 m from the Kalavista boat launch. Core Sites 3 to 5 were along the shore in areas with multiple private docks, high boating activity, and stormwater outfalls. Core Sites 3 and 4 were collected about 100 m offshore in 5 – 10 m of water, while Core 5 was collected 40 m offshore in 11 m of water. Surface core layers were analyzed for metals, hydrocarbons, and bacteria, while subsections of deeper core layers were analyzed for metals to determine changes over time. The age of sediment deposition increases with core depth so shallower sediments were more recently deposited.

For the boating impact study (Schleppe et al., 2017), sediment cores or dredge samples were collected at several marinas and sites in Kalamalka Lake; this data and sampling methodology informed the 2018 sediment study but was not repeated (Appendix 3).

Table 2-1: 2018 Sediment core sample site locations and parameters measured

Core Site Name	Latitude	Longitude	Water Depth (m)	Distance from shore(m)	Core depth (cm)	Total Metals	E. coli	Hydro-carbons
Core 1 marina upper	50.222945°	-119.263985°	6-8	85	0-20	X	X	X
Core 1 marina lower			6-8	85	20-40	X		
Core 2 Kalavista upper	50.227981°	-119.266098°	4	92	0-10	X	X	X
Core 3 dock N upper	50.230131°	-119.269493°	5	125	0-15	X	X	X
Core 3 dock N lower			5	125	15-25	X		
Core 4 dock mid upper	50.228768°	-119.276742°	10	100	0-20	X	X	X
Core 4 dock mid lower			10	100	20-40	X		
Core 5 dock S upper	50.226454°	-119.279741°	11	40	0-15	X	X	X
Core 5 dock S mid			11	40	15-30			
Core 5 dock S lower			11	40	30-40	X		
Core 6 Coldstream Ck	50.224407°	-119.262160°	0.1	-	-	X		

* at 2.9 mm/yr (Dill 1972), 10 cm would take 34.5 years to accumulate at sites not affected by Coldstream Ck

All sediment samples were analyzed for total metals, *E. coli*, and hydrocarbon contamination by CARO Analytical, Kelowna. The reportable detection limits for sediment metals of interest (total metals mg/kg) were: Aluminum Al 50, Antimony Sb 0.1, Arsenic As 0.1, Barium Ba 0.5, Beryllium Be 0.2, Cadmium Cd 0.02, Calcium Ca 50, Chromium Cr 0.5, Copper Cu 0.5, Iron Fe 50, Lead Pb 0.5, Lithium Li 5, Magnesium Mg 20, Manganese Mn 1.0, Mercury Hg 0.1, Molybdenum Mo 0.1, Nickel Ni 0.5, Phosphorus P 50, Potassium K 100, Selenium Se 0.2, Silver Ag 0.1, Sodium Na 50, Tin Sn 2, Uranium U 0.05, Zinc Zn 2.

2.2 Sediment Trap Collection

Sediment traps measure the rate at which sediment falls out of the water column and accumulates on the lake bottom. Ten pairs of sediment traps were deployed along the shore of the North Arm on June 5 and recovered on October 18, 2018 (135 days, Figure 3-8). The purpose of these traps was to measure the sedimentation rate within the North Arm during the main boating season, determine if there is a geographic pattern to the accumulation rate, and to compare that rate to those expected in other marl lakes.

They were deployed in 5 to 25 m depth distributed around the North Arm (Table 2-2). The traps were suspended approximate 1 m above the sediment at each site. Sediment traps contents were sent to CARO Labs for analyses of total volatile solids (a measure of organic content), dry weight (a measure of total mass), and total metals. We also considered the data from sediment traps deployed for the Boating Study during the peak boating period in the summer (July 29 – Oct 7, 2016).

Table 2-2: 2018 Sediment trap locations

Sediment trap name 2018	Trap location	Latitude	Longitude	Water Depth (m)	Distance from shore(m)	Total Metals	Dry wt & volatile solids
Sed Trap 1	Near marina	50.222724°	-119.264064°	5	80	X	X
Sed Trap 2	Ck mouth	50.223808°	-119.263758°	10	34	X	X
Sed Trap 3	Ck plume	50.224085°	-119.264425°	10	33	X	X
Sed Trap 4	Ck plume	50.225219°	-119.265697°	10	150	X	X
Sed Trap 5	Ck plume	50.226276°	-119.266674°	10	190	X	X
Sed Trap 6	Kalavista	50.228272°	-119.267299°	10	175	X	X
Sed Trap 7	Off outfalls	50.229068°	-119.269196°	10	235	X	X
Sed Trap 8	Near intake	50.227191°	-119.274565°	25	300	X	X
Sed Trap 9	Deep	50.228425°	-119.273494°	10	165	X	X
Sed Trap 10	Residential	50.228147°	-119.277928°	10	115	X	X

As part of the 2016 Boating Study, LAC conducted sediment and bacterial fall tests to determine the time required for sediment and bacteria to settle out of the water column and deposit on the substrates. Please refer to the Boating Study report for these methods (Schleppe 2017; Appendix 4).

3.0 Results and Discussion

3.1 Sediment Core Results

Sediment cores were collected at five lake sites and one site within Coldstream Creek. and were distributed along the shoreline of the North Arm focusing on sites offshore from areas of high potential impact (Figure 3-1). None of the sediment core sites were directly adjacent to shoreline contamination sources; rather, they were located in areas of high boating activity within 40 - 125 m of the shoreline and should therefore reflect sediment re-distribution by turbulence.

Figure 3-1: Map of Sediment core locations in North Arm of Kalamalka Lake

3.1.1 Sediment Core Metals

Earlier Kalamalka sediment metal studies demonstrated that anthropogenic metals (e.g. Zn, Al, Pb, As) in North Arm sediments were 2 to 3 times the concentration in South Kalamalka sediments. These results are attributable to the greater urban development and agriculture through the Coldstream Valley (Larratt, 2001; Schleppe et al., 2017).

This 2018 study shows interesting patterns of metal accumulation within the past few decades. There was a clear difference in sediment marl concentrations from samples collected close to the mouth of Coldstream Creek and those collected a distance from it. Lake sediments were very high in the marl constituents calcium and sulfur, while sediments within Coldstream Creek and its plume paths were low in these parameters

(Figure 3-2). As a result, Core Sites 1, 2, and 3 show varying degrees of creek sediment deposition, while Core Sites 4 and 5 are more typical of shallow Kalamalka Lake marl sediments.

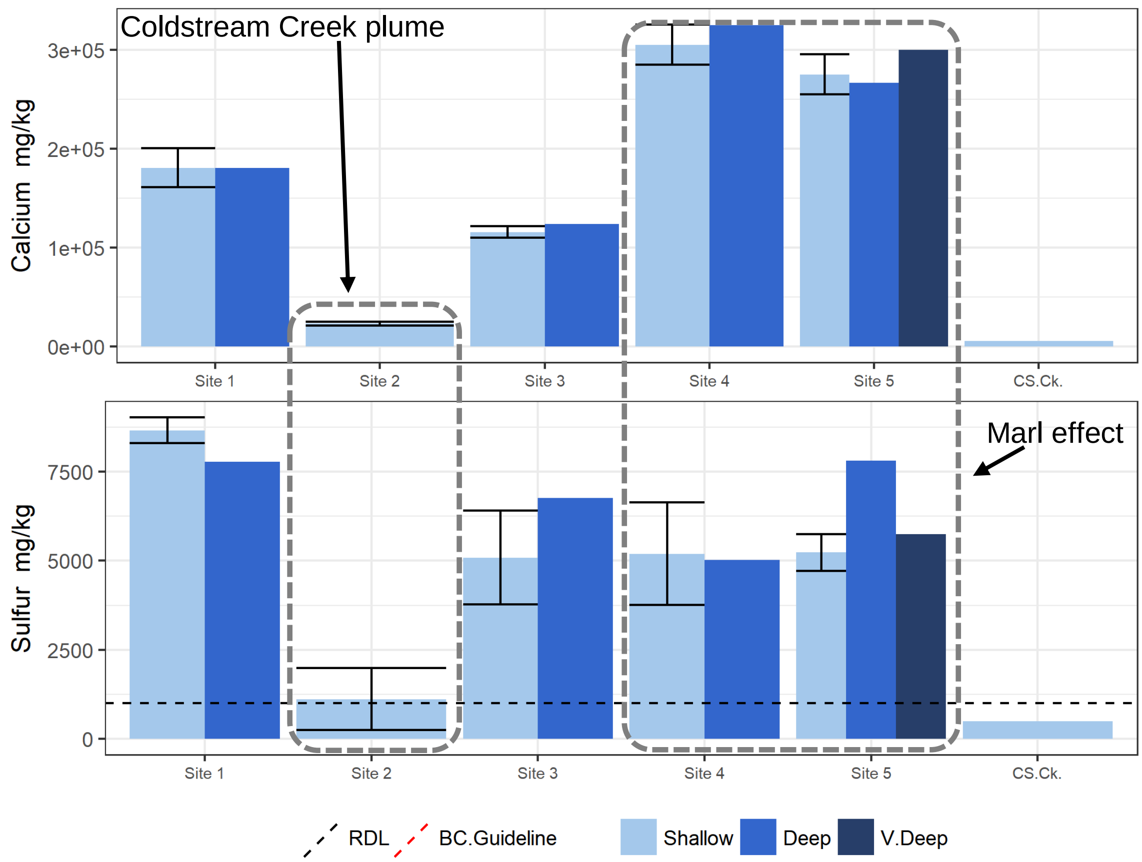

Figure 3-2: Calcium, and sulfur concentrations in Kalamalka Lake sediment cores
Note: BC MoE sediment guidelines are off the scale, i.e. values were far below the guideline

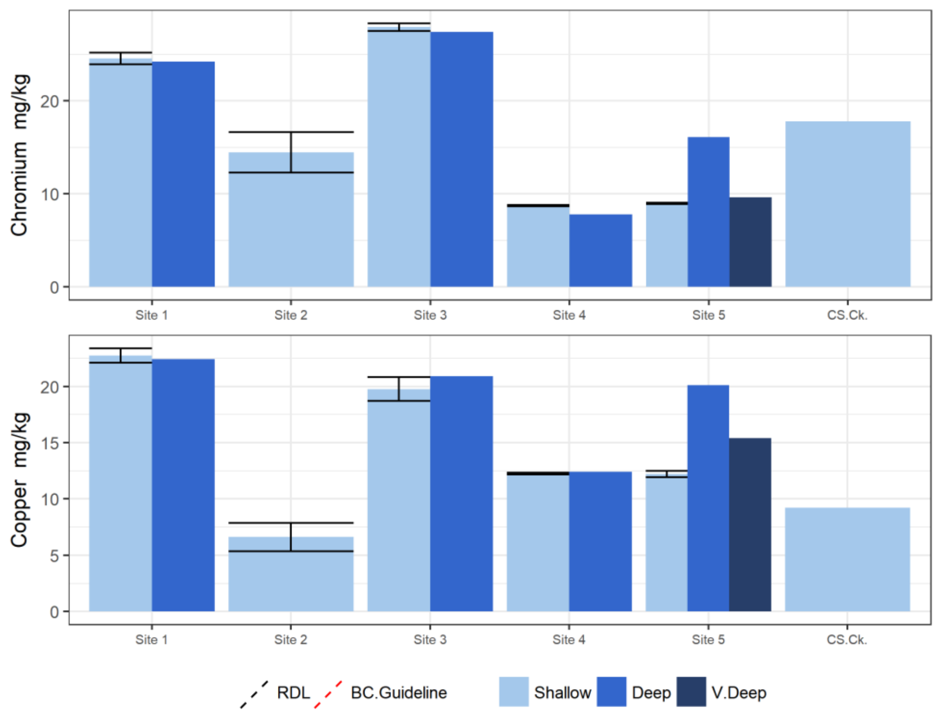

Figure 3-3Cores 1 (adjacent to marina) and 3 (adjacent to stormwater outfalls at north-west end of lake) located along the shoreline Coldstream Creek plume path contained elevated values for antimony, arsenic, beryllium, cadmium, chromium, copper, iron, lead, lithium, magnesium, nickel, potassium, and zinc, compared to other sites (Figure 3.3 Appendix 1)

These metals are associated with human activities (Soil and Water Conservation Society of Metro Halifax (SWCSMH), 2016). The comparatively higher metal concentrations at Core sites 1 and 2 indicate a history of greater human activity impacts. There are numerous stormwater outfalls in the North Arm (Figure 3-6). Stormwater discharges commonly carry many of these metals (Jang et al., 2007; Rangsivek & Jekel, 2005). The elevated metals from North Arm cores were also highly correlated indicating that they have a common source (Appendix 2: Metals Correlation Results). Coldstream Creek has a dominant impact on the North Arm as it conveys both urban stormwater and agricultural land runoff.

Sandy sediments from the Coldstream Creek bed (Core 6) and shoreline plume path (Core 2) were nearly identical – they had lower metal concentrations that were comparable to Cores 4 and 5. Sand settles out quickly and would affect Core 2, while Cores 1 and 3, just outside the freshet plume, would accumulate silt that has a greater surface area for adsorbed metals. Metals results from the 2018 sediment traps support this theory because the trapped metals showed metals accumulation along a distance gradient from the Coldstream Creek plume paths (Figure 3-12).

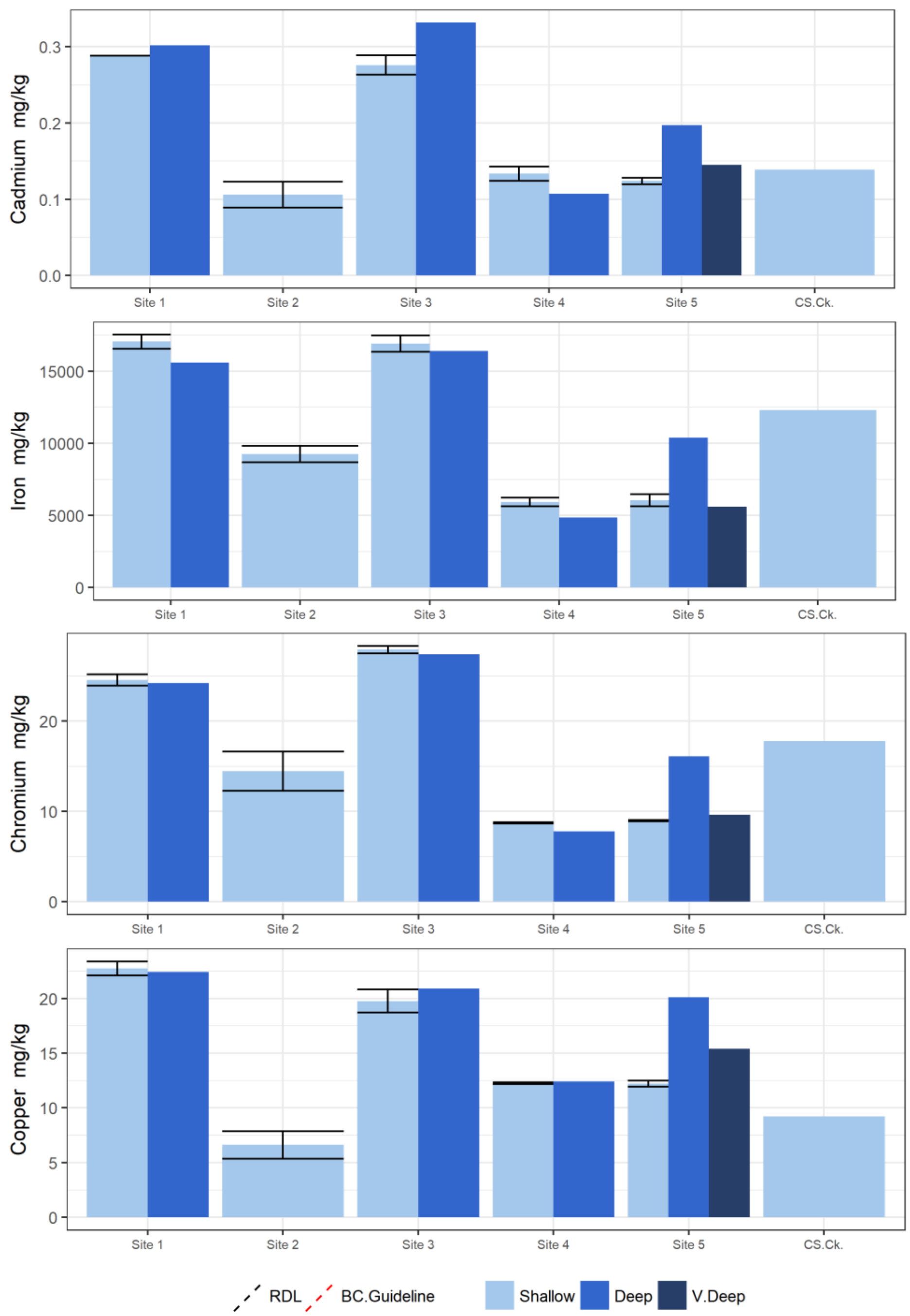

Figure 3-3: Cadmium, chromium, copper, and iron concentrations in Kalamalka Lake sediment cores

Note: BC MoE sediment guidelines are off the scale, i.e. values were far below the guideline

Lead was elevated at Core Site 3 in both shallow and deep sediments and was similar at the other five sites (Figure 3-4). Lead did not exceed the BC MoE sediment guideline (35 mg/kg) at any site. Lead is a legacy pollutant that was restricted or banned in the 1970s. Downward trends of these legacy pollutants have been noted since they were banned in most jurisdictions; however, residual lead sources remain in the urban environment.

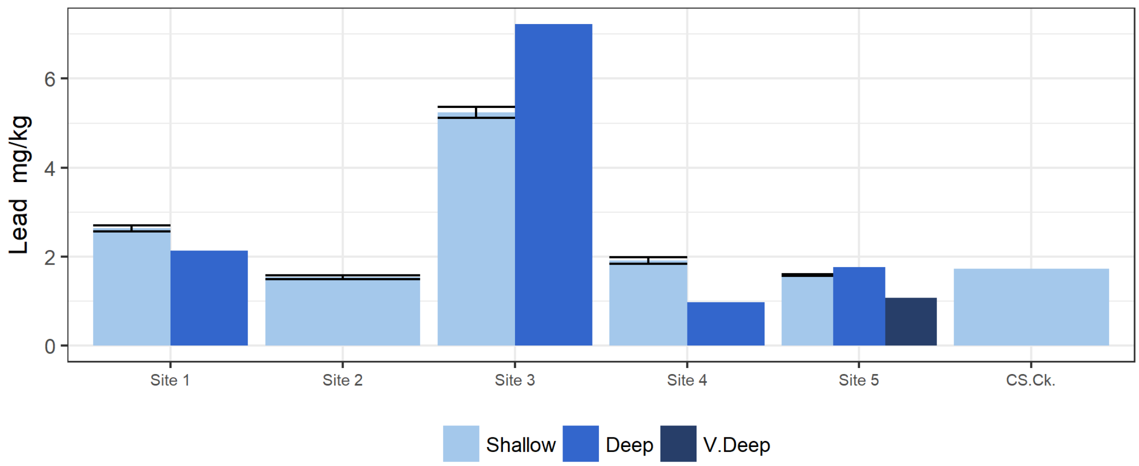

Figure 3-4: Lead concentrations in Kalamalka Lake core sediment samples
Note: BC MoE sediment guideline is above the scale on this graph, i.e. values were far below the guideline

In the sediment core samples, only nickel exceeded the BC MoE sediment guidelines (Figure 3-5). The results exceeded the guideline by 1-3%; however, nickel is both persistent and toxic. In flowing water, nickel is transported mainly as a precipitated coating on particles and in association with organic matter (Cempel and Nickel 2006). This could explain why the exceedances occurred at Cores sites 1 and 3 that flank the shoreline Coldstream Creek plume path, where fine sediments and organics would deposit. Additionally, Core Sites 1 and 3 could receive Ni from a marina and stormwater outfalls, respectively, that are both well-known Ni sources (NCDEM, 1991).

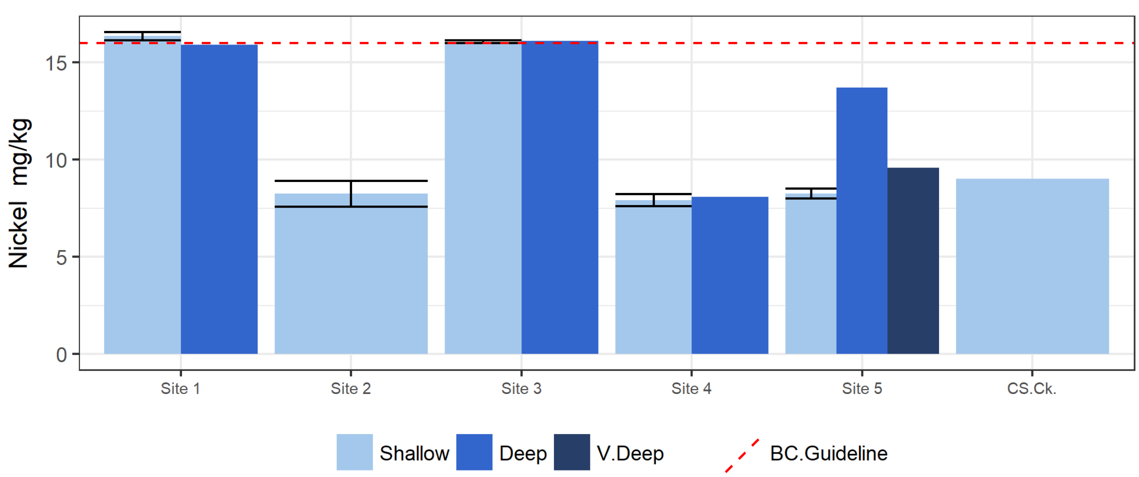

Figure 3-5: Nickel concentrations in Kalamalka Lake sediments

There was no significant difference in metals content between the shallow samples (deposited in recent decades) and deeper sediments that were deposited approximately >30 years ago. These results show that urban and agricultural activities continue to influence metal deposition in the North Arm of Kalamalka Lake.

3.1.2 Hydrocarbons in Sediment Cores

Polyaromatic hydrocarbons (PAHs) and fuel additives are a concern in drinking water, even at low concentrations (Asplund, 2000). Spills are the leading cause of hydrocarbon contamination of lake sediments (BC WQG). While straight-chain hydrocarbons can be volatilized or decomposed, PAHs are persistent in the aquatic environment. PAHs are characterized by high lipophilicity (accumulate in food chains), high hydrophobicity (accumulate in sediments) persistence, and unfortunately, high toxicity (Lima et al 2005). The presence of organic carbon in sediments plays a dominant role in the distribution of PAHs (Herngren et al. 2010). Since lake sediments act as a contaminant reservoir, sediment disturbance can return PAHs to the water column when they otherwise are only detected in water samples during the active boating season (Mastran et al. 1994).

The hydrocarbon results in this study were similar to the results from the 2016 Kalamalka Lake Boating Capacity Study (Schleppe et al., 2017). Both studies found hydrocarbons to be below detection at Core Site 2 (offshore of Kalvista boat launch) – results that are likely attributable the low retention of hydrocarbons in coarse/sand gravel substrates (insert supporting reference) found at that site. Hydrocarbons were also not detected at Core Site 1, which was collected 85 m offshore from a small marina. Hydrocarbon contamination is, however, typical in marinas (Mastran et al., 1994; Nelson 2009). Although we did not repeat marina sampling from the 2016 Boating Study, the elevated sediment hydrocarbons at the Oyama Canal, Turtle Bay Marina, and T'ween Lakes Marina (Schleppe et al., 2017) already confirmed hydrocarbon contamination of the fine clayey substrate that collects in these marinas. Fines accumulate at marinas through disruption of longshore currents. The fine texture and organic content of the sediment at the canal and marina locations increases retention of hydrocarbons, and the effects of hydrocarbons are amplified by power boats that re-suspend fine sediments into the water column. Regardless of their source, boat wake and wave re-suspension of these persistent and toxic sediment contaminants is a concern.

North Arm sediment core samples were analyzed for hydrocarbon contamination and only Site 3 had detectable values. The following PAHs were detected at Core Site 3: Benz(a)anthracene, Benzo(a)pyrene, Benzo[j]floranthene, Chrysene, Fluoranthene, Phenanthrene, and Pyrene. These compounds are associated with incomplete fuel combustion and are persistent (Nagpal, 1993; Rempel et al 2018). Some of these compounds exceeded their respective CCME sediment guidelines for the protection of aquatic life and these are highlighted in Table 3-1. The likely source of these PAHs is stormwater from a series of nearby outfalls, and possibly from intensive power boating that occurs near Core Site 3. Core Site 3 also showed elevated heavy metal concentrations including lead. These results suggest that this site is more impacted than the others.

All PAHs detected in Kalamalka sediments are associated with incomplete fuel combustion, roadway sealants and wood fires. Stormwater discharges bearing oils, grease, and coal tar from roadway sealants together with PAHs from gasoline combustion would influence sediments along their plume paths (Gunawardena et al. 2014). Even within marinas, stormwater outfalls are associated with very high PAHs in sediments along the stormwater plume path (Neira et al. 2017). PAHs build up on road surfaces primarily from gasoline-powered vehicles (Gunawardena et al. 2014). A sample of stormwater in a Kalamalka Lake outfall contained extractable petroleum hydrocarbons (LEPH + HEPH) (Summit 2012), demonstrating the presence of hydrocarbons in local road stormwater; however, PAHs were not detected in this sample. Other potential PAH sources such as forest fires should cause a more even distribution within the sediments because of the region's long history of fires.

The combinations of PAHs present in a sample can be compared against known PAH fingerprints to help identify sources. Using this method, the source of PAHs at Core Site 3 is likely stormwater (Figure 3-6) (Lima et al., 2005; Mohamad Pauzi Zakaria et al., 2002; Stogiannidis & Laane, 2014, Reible et al 2018). In contrast, the source of elevated PAHs in the marina and canal sediments indicated boat fuel impacts. Localized marina boating impacts have been found to elevate phenanthrene, fluoranthene, and pyrene PAH profiles (Mastran et al 1994); these are the PAHs that exceeded sediment guidelines in the marina and canal sediments (Table 3-1).

Table 3-1: Hydrocarbon results of this study compared to the 2016 Boating Study

	Kalamalka Lake 2018 Sediment Study					2016 Kalamalka and Wood Lake Boating Study			
	Core Site 1	**Core Site 2**	**Core Site 3**	**Core Site 4**	**Core Site 5**	**Oyama Channel**	**Kal South Marina**	**Kal N Boat Launch (Site 2)**	**Wood Lake Marina**
EPHs19.32	<76	<50	<74	<76	<80	**250**	**890**	<50	**670**
HEPHs	<76	<50	<74	<76	<80	**250**	**890**	<50	**670**
Benz(a)anthracene	<0.065	<0.050	**0.071**	<0.075	<0.080	<0.05	<0.1	<0.05	<0.1
Benzo(a)pyrene	<0.065	<0.050	**0.063**	<0.075	<0.080	<0.05	<0.1	<0.05	<0.1
Benzo[*b*+*j*]fluoranthene	<0.065	<0.050	**0.059**	<0.075	<0.080	<0.05	<0.1	<0.05	<0.1
Chrysene	<0.065	<0.050	**0.088**	<0.075	<0.080	**0.05**	<0.1	<0.05	<0.1
Fluoranthene	<0.065	<0.050	**0.091**	<0.075	<0.080	**0.18**	**0.16**	<0.05	<0.1
Phenanthrene	<0.065	<0.050	**0.176**	<0.075	<0.080	**0.11**	<0.1	<0.05	<0.1
Pyrene	<0.065	<0.050	**0.144**	<0.075	<0.080	**0.15**	0.17	<0.05	**0.13**

Source: 2016 Kalamalka and Wood Lake Boating Study (Schleppe et al, 2017)
Note: Red values indicate exceedances of CCME sediment guidelines for protection of aquatic life
EPH = extractable petroleum hydrocarbons HEPH heavy extractable petroleum hydrocarbons

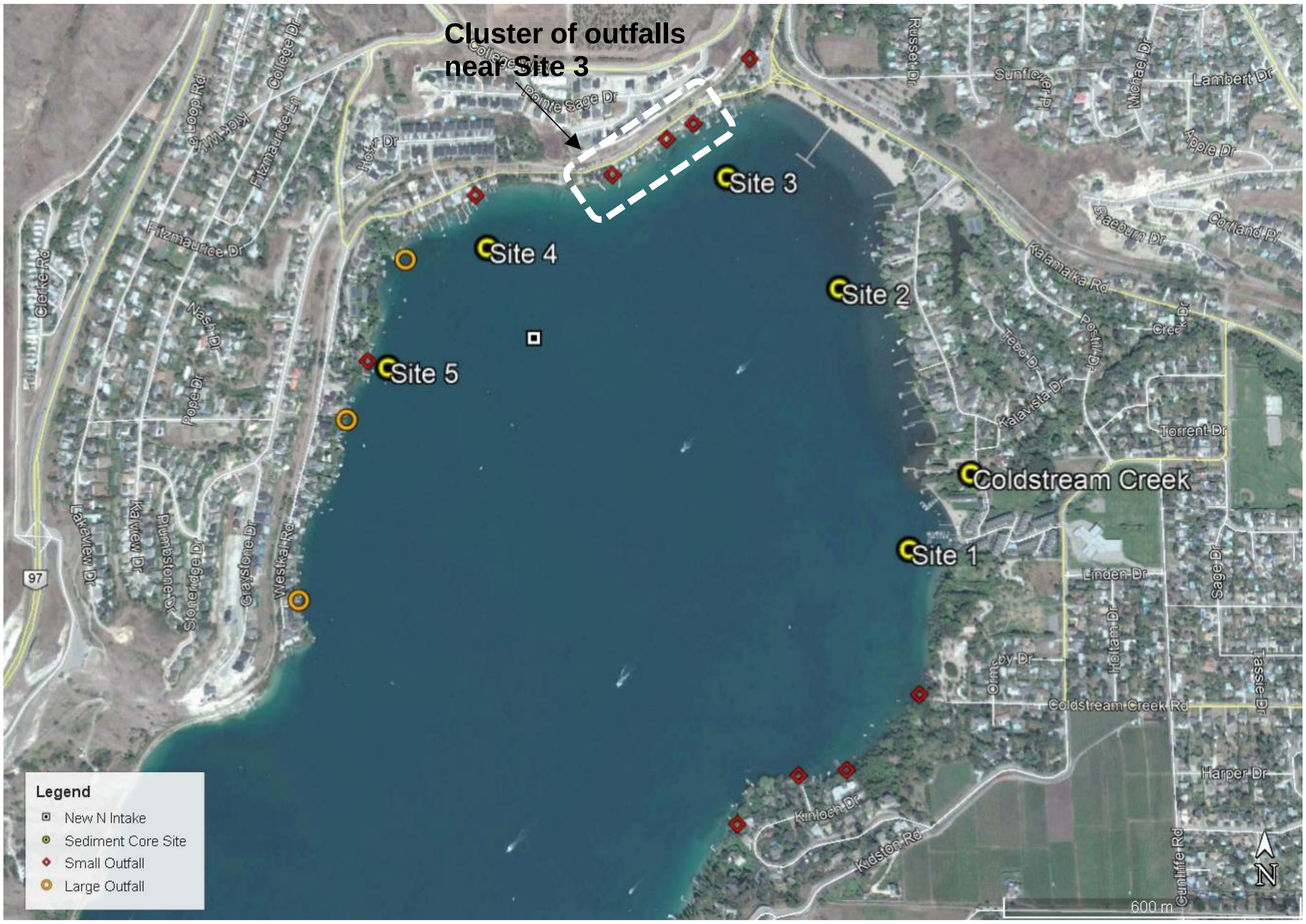

Figure 3-6: Stormwater outfalls in the North Arm of Kalamalka Lake and sediment core sites

3.1.3 Sediment Core Bacteria

The upper sediment core samples were also analyzed for total coliforms and *E. coli*. We expect more viable bacteria in the upper 1-2 cm of sediment (recently deposited) because these bacteria can remain viable for weeks on sediment grains, but not years (Ishii et al 2007). Analysis of the upper 10-20 cm of the cores would “dilute” the counts, so trends are more relevant than counts in the core samples. Please refer to Section 3.2.3 for the sediment trap bacteria results.

Total coliforms are soil bacteria and the elevated concentration at Core Site 2 is likely related to Coldstream Creek or discharge from the Kalavista Lagoon (Figure 3-7). *E. coli* are found in human and animal feces. Numerous samples and studies of Coldstream Creek flows have demonstrated consistent *E. coli* exceedances of >100 with spikes to >15000 MPN/100mL (BC MoE; Larratt and Self 2017). Despite this, sediment samples collected from the plume path had low *E. coli* counts. *E. coli* were detected at Core Site 5 and likely relate to the small stormwater outfall nearby (Figure 3-6, Figure 3-7). The Stormwater study found elevated summer *E. coli* counts of 460 – 11000 MPN/100mL in North Arm stormwater outfalls (Summit 2012). *E. coli* were near the detection limit at the remaining North Arm sites (Figure 3-7).

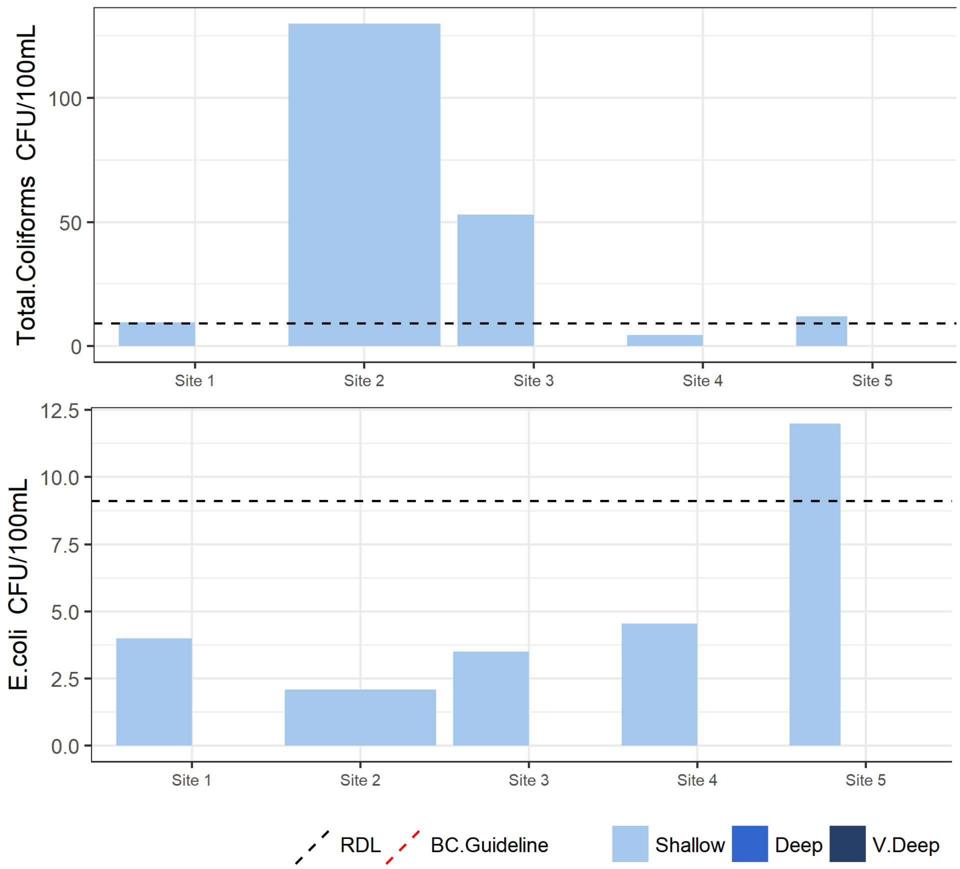

Figure 3-7: Total coliforms and *E. coli* in Kalamalka Lake sediment cores
Note: Black dashed line represents reportable detection limit.

3.2 Sediment Trap Results

Sediment caught in the traps represents newly deposited sediments or redeposition of disturbed substrates in summer 2018 (Figure 3-8). The purpose of these traps was to measure the sedimentation rate within the North Arm during the main boating season,

Figure 3-8: Sediment trap locations within North Arm, Kalamalka Lake

3.2.1 Accumulation Rates

Sediment accumulation rates were calculated at each of the ten sediment trap sites (Table 3-2). The average accumulation rate for all sites was 0.353 ± 0.970 g/m²/day during the trial period. This is high compared to Okanagan Lake (0.06 – 0.17 g/m²/day based on other work by LAC) and low compared to other marl lakes (~1.0 g/m²/day)(Rose et al., 2011; Wiik et al., 2015). These results were lower than those measured in the 2016 Kalamalka Lake boating capacity study (1.65 g/m²/day and 1.08 g/m²/day for shallow and deep traps respectively) indicating year-over-year variation in the sedimentation rate. The highest accumulation rate for both total and organic material occurred at Trap Site 2 in Coldstream Creek's main plume path, which averaged 2.16 g/m²/day over the five-month trial period. There was high variability between the sediment traps at Trap Site 2 where they collected 10.2 g and 0.67 g of material respectively.

Trap Site 8 (adjacent to N-Kal intake) averaged 0.78 g/m²/day and was the second fastest total and volatile sediment accumulation rate. Unlike Trap Site 2, the sample pairs at Trap Site 8 were similar. Site 8 was the deepest (25 m depth) and likely experienced some sediment focusing, a process whereby sediments migrate from the shallows into deeper water. Mobilized sediments are more likely to reach deeper water when lakebed slopes are greater than 4% (Brown et al., 1992; Hakanson 1977).

In shallow areas of Kalamalka Lake, sediments are mobilized by wave action and by boat wakes. Since the slope in areas from 2 m to 23 m in Kalamalka Lake is 5%, liberated sediments should begin downward migration towards the RDNO intake. Some of the sediment in the deep sediment traps at Site 8 would have originated from the shallows and was not entirely the result of whole-lake phenomena such as marl precipitation and settling of algae cells.

Trap Site 1 (offshore from a small marina) and Trap Site 6 (off shore from a boat launch) were the closest to major boating activities and should be most affected by boating. Trap Site 2 was affected by both boating idling/powering and the creek plume, while Trap Sites 3 through 5 should be most affected by Coldstream Creek (Table 3-2). No statistically significant difference in sediment accumulation occurred between these groups of sites. This may be in part because of differing sediment types. For example, sediments near the boat launch are sand/gravel and less prone to re-suspension than marl sediments. However, there was a declining sediment accumulation trend with distance from the mouth of Coldstream Creek (Sites 4-6). This pattern is expected as progressively finer sediments settle out of the creek plume.

Table 3-2: Average sediment accumulation rates in Kalamalka Lake North Arm from June to October 2018

Sed. Trap Site	Dry Weight g dry	Total Volatile Solids g dry	% Volatile %	Total Accumulation Rate g/m²/day	Volatile Accumulation Rate g/m²/day
1	0.008	0.006	73%	0.003	0.003
2	5.125	0.338	12%	2.170	0.143
3	0.007	0.002	29%	0.001	0.000
4	0.698	0.061	9%	0.295	0.026
5	0.528	0.052	11%	0.223	0.022
6	0.124	0.017	44%	0.052	0.007
7	0.004	0.004	100%	0.001	0.001
8*	1.845	0.249	14%	0.781	0.106
9	0.007	0.004	57%	0.001	0.001
10	0.004	0.003	73%	0.002	0.001

Notes:

- Sites most likely to be affected by boating highlighted in blue, Site most likely to be affected by Coldstream Ck. highlighted in yellow. Sites affected by both are in green
- Volatile solids are the organic fraction of the sediment and include bacteria, algae, plant material, invertebrates, and other decomposing organic material
- *Site 8 is a deep water site located adjacent to the intake that will likely experience some sediment focusing that would increase its sediment accumulation rate.

The highest total and volatile (organic) solids accumulation rates occurred at Trap Site 2 located within the main Coldstream plume. The second highest sediment accumulation rate occurred at Trap Site 8, adjacent to the intake. The % volatile in this data is relatively high and reflects the organic imports from Coldstream Creek and to some extent organic production (algae) in the North Arm (Desloges 1994; Kemp et al., 1972).

Sediment fall tests were conducted as part of the 2016 Kalamalka Lake boating capacity study (Figure 3-9; Schleppe et al., 2017). Kalamalka Lake marl sediments from shallow areas and silty sediments from deep areas left a haze in the water column for over 6 days, indicating that fine particulates and their associated contaminants could remain suspended even in still water. Clearly, many North Arm Kalamalka Lake sediments are susceptible to re-suspension and can return associate contaminants to the water column for a week. Extremely small particles of marl or bacteria cells will take much longer than a week to settle (Schleppe et al, 2017).

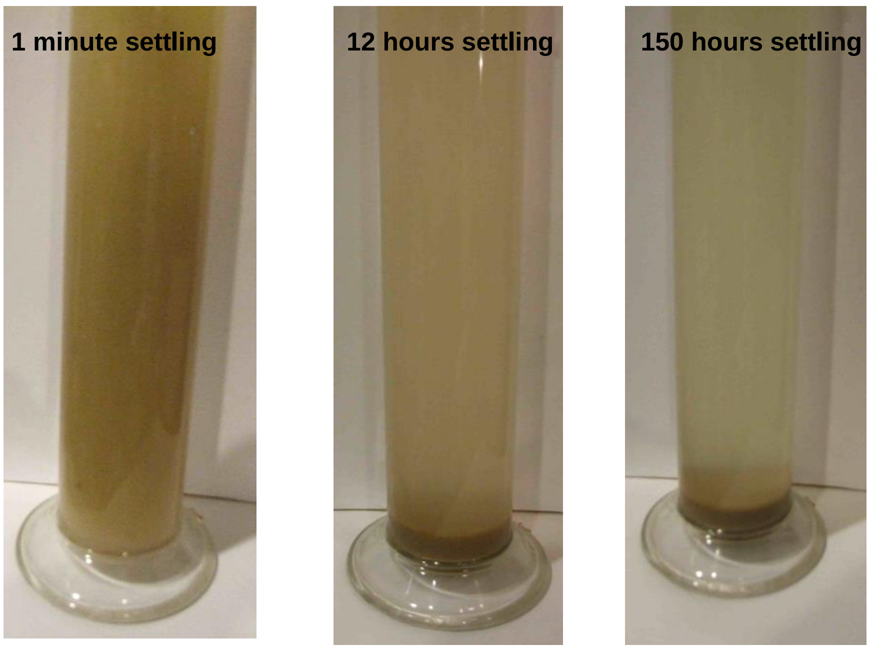

Figure 3-9: Photographs of shallow marl sediment fall tests after 1 minute, 12 hours, and 150 hours

Overall, Coldstream Creek sediment deposition appears to be a key driving factor in sediment accumulation throughout the North Arm. The highest deposition rates occurred near the creek mouth where coarse sediments settle quickly, while silts and organics were distributed further by the creek plume. In contrast, boating wake turbulence is more likely to cause localized but significant short-term disturbance on shallow silty or marl substrates. Re-suspension of these fines by turbulence contributes to sediment travelling to deep areas and resulted in high sedimentation rates measured adjacent to the water intake. The Boating Study found activities that disturb large areas of fine sediment such as rototilling or wakeboard/wakesurf boats in water shallower than 4-5m can generate a turbidity plume (Schleppe et al, 2017).

3.2.2 Sediment Trap Metals

The sediment trap material was analyzed for metals to give an indication of metals accumulating within the North Arm during 2018. The metal concentrations were similar to the sediment cores, but the effect of Coldstream Creek was more distinct. Marl-associated metals such as calcium were lowest around the mouth of Coldstream Creek (Figure 3-10).

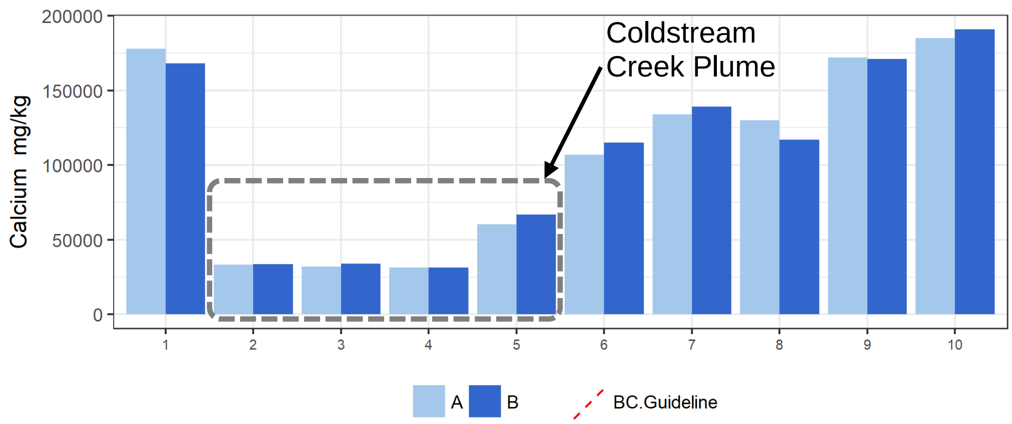

Figure 3-10: Calcium concentration in sediment collected in sediment traps in North Arm Kalamalka Lake

The distribution of several metals followed a similar pattern indicating Coldstream Creek was the likely source (Figure 3-11;Figure 3-12; Figure 4-5). These metals included: aluminum, antimony, arsenic, beryllium, cadmium, chromium, cobalt, copper, iron, lead, lithium, nickel, potassium, silver, thallium, thorium, titanium, vanadium, zinc, and zirconium. There was a clear increase in these metals at Trap Sites 2 through 6 that have been identified as being within the Coldstream Creek plume in other research (Larratt and Self 2017). Chromium, copper, iron, and nickel exceeded their BC MoE sediment guidelines at several sites with Sites 4 and 5 having the highest concentrations. There were more exceedances in the sediment trap data than the sediment cores, which means that heavy metal loading into Kalamalka Lake sediments is an ongoing concern.

Trap Site 8, positioned adjacent to the Kalamalka Lake intake in 25m of water (Table 2-2), had higher metal concentrations than the surrounding shallow sediment traps (Sites 9 and 10, Figure 3-12). This is likely because of sediment focusing in deeper water and a greater proportion of fine sediments, which adsorb more metals than coarse sandy sediment (Kuriata-Potasznik et al., 2016; SWCSMH, 2016). This result emphasizes not only the importance of the heightened intake clearance (from 0.6 m to 3.5 m) for improved protection from suspended sediments, but also the issue raised by sediment deposition or re-suspension in the North Arm.

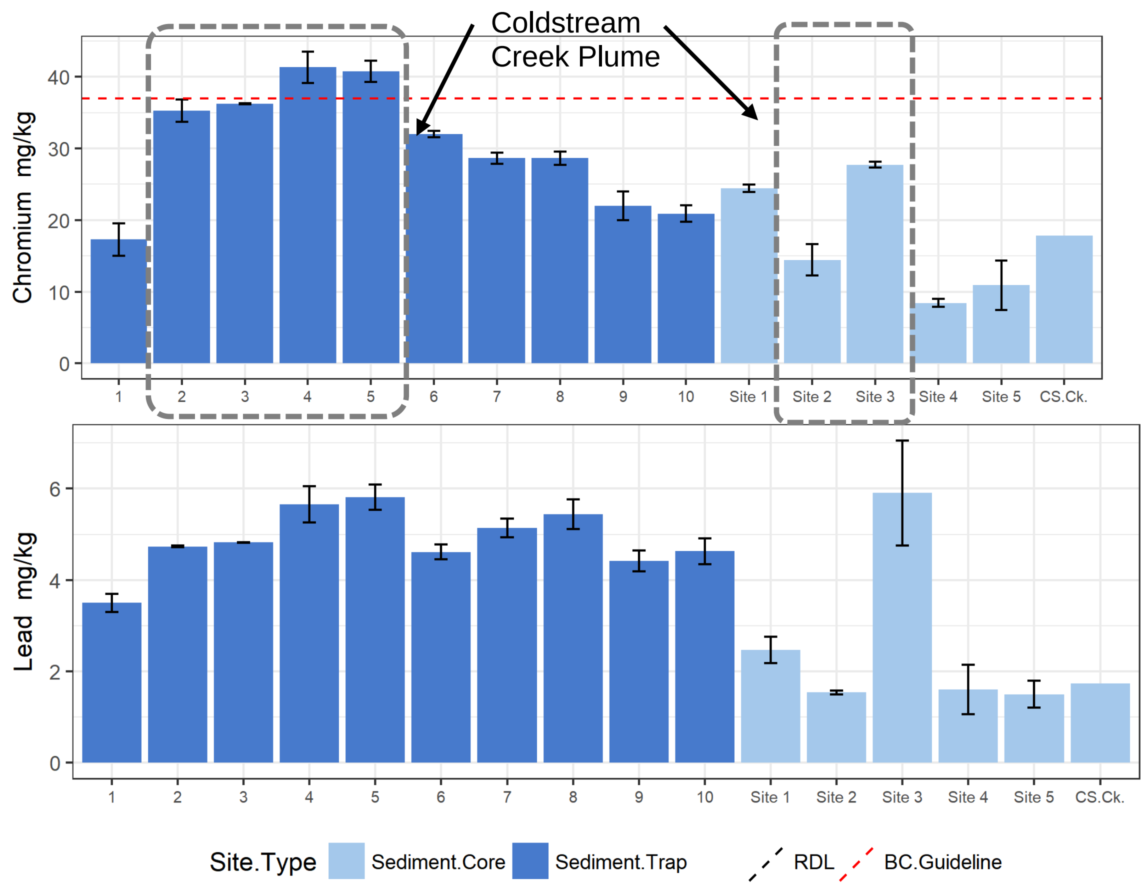

Figure 3-11: Comparison of chromium and lead concentrations in the sediment cores (historical accumulation) and sediment traps (2018 accumulation)

Note: Reportable detection limit (RDL) not displayed on these graphs because all samples had detectable values. Please refer to Methods for metal RDL's

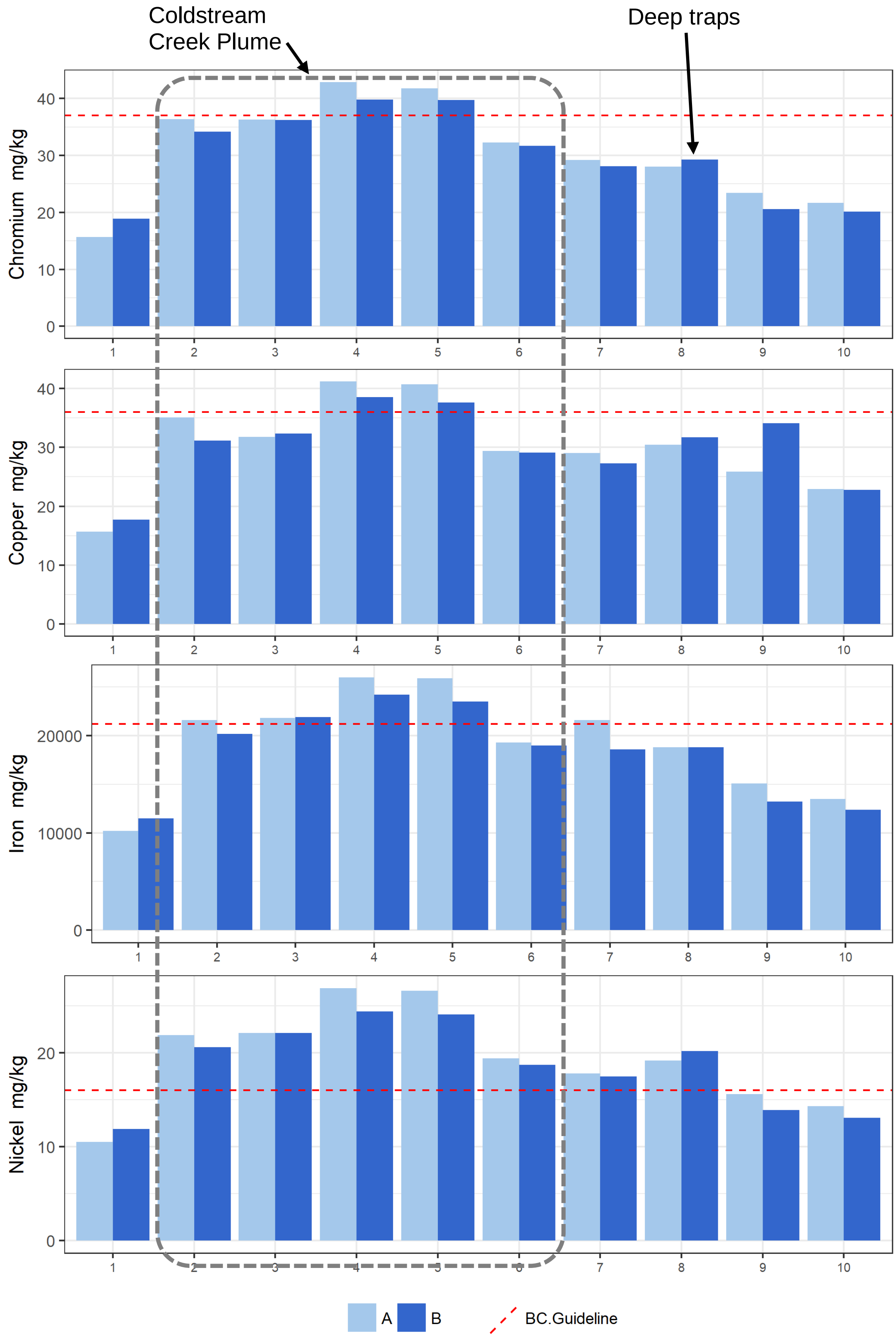

Figure 3-12: Chromium, copper, iron, and nickel concentrations in sediment captured in Kalamalka Lake sediment traps
Note: A and B are the left and right sample pair of each sediment trap

3.2.3 Sediment Trap Bacteria

Fecal bacteria concentrations were measured in the sediment captured in the sediment traps. Counts were elevated at Trap Site 7 and 8. High *E. coli* counts in the sample from Site 8 – the closest to the RDNO drinking water intake – unfortunately indicate ongoing bacterial accumulation near the intake. A marker buoy installed near the intake in 2016 has become a popular resting spot for birds (Figure 3-14). It is possible that feces from these birds are the main source of the elevated *E. coli* counts at Trap Site 8. Alternately, sediment disturbance from shallower contaminated sediments can transfer bacteria to deeper locations. In any case, the elevated counts near the RDNO intake is concerning. For Trap Site 7, the source of fecal bacteria is likely a nearby cluster of stormwater outfalls (Section 3.1.2). Sediment trap Site 10 was also in the deep intake area and again, showed higher bacteria counts than the other North Arm sites over summer 2018. Finally, Trap Site 3 is also adjacent to stormwater and Coldstream Creek plume, and it had more fecal bacteria than background sites. High concentrations of fecal coliforms and *E. coli* were detected in North Arm stormwater in other work (Summit 2012, Kerr Wood Liedel 2016). These counts are important because the sediments can act as a bacterial reservoir and return viable bacteria to the water column during turbulence (Ishii et al, 2007; Laliberte and Grimes 1982).

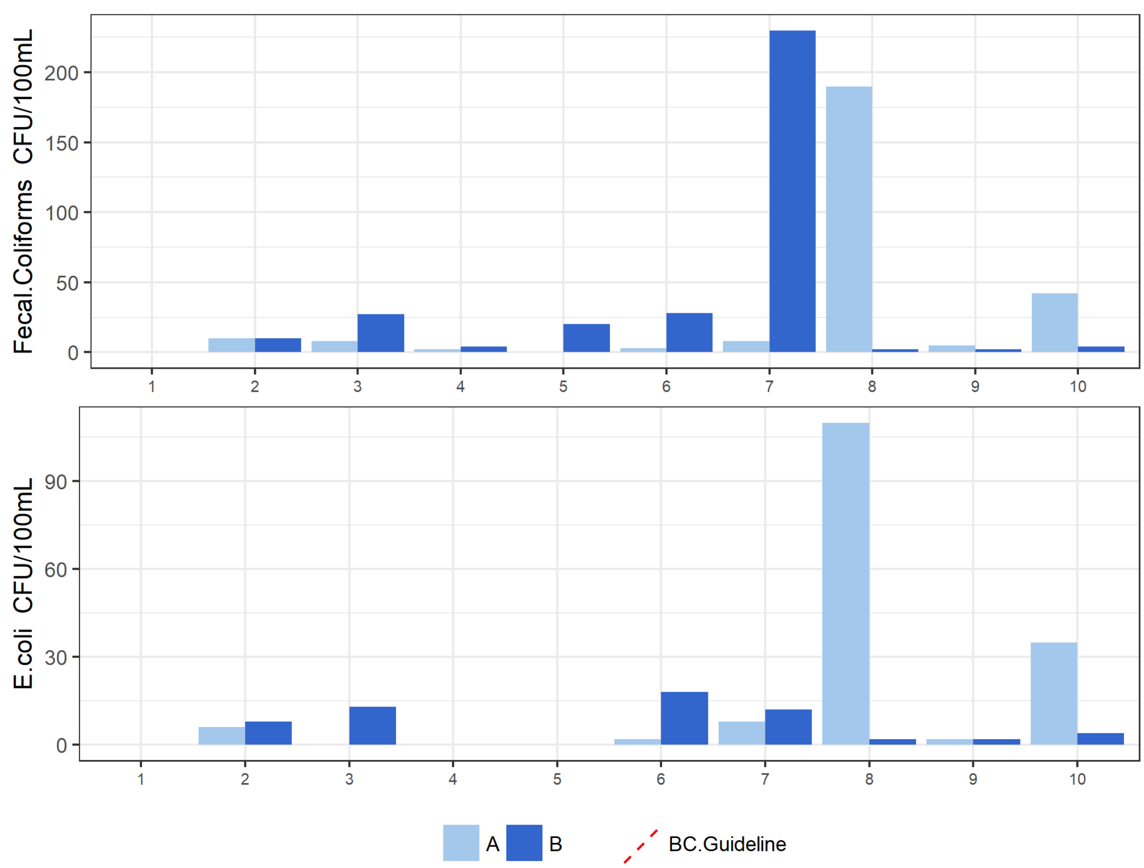

Figure 3-13: Fecal bacteria concentrations in sediment captured in Kalamalka Lake sediment traps during 2018

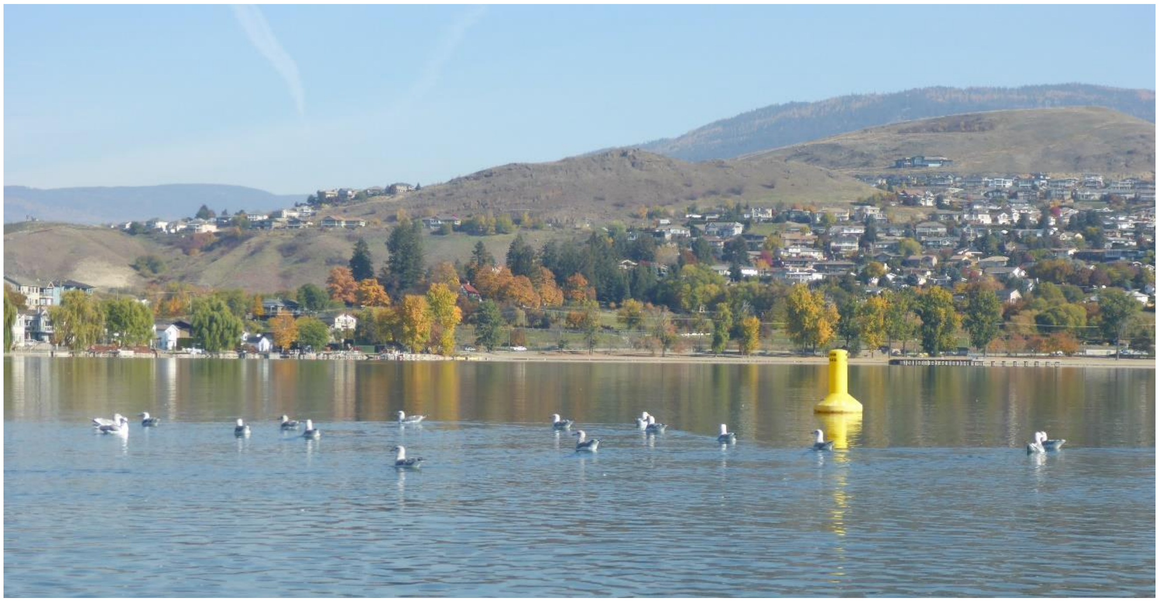

Figure 3-14: Seagulls resting near the marker buoy for the RDNO Kalamalka Lake drinking water intake

Sediment bacteria samples are periodically collected at the intakes as part of ongoing monitoring for the RDNO intake. These results are reported in the annual Kalamalka Lake Monitoring report for RDNO and DLC. In September 2018, the north Kalamalka Lake samples contained 34 CFU/100mL of *E. coli* while the south Kalamalka Lake samples contained only 9 CFU/100mL of *E. coli.* The higher *E. coli* counts in the North Arm are attributable to Coldstream Creek and the numerous stormwater outfalls located there. The sediment trap data were also elevated at the intake (Site 8) with 110 CFU/100mL (Figure 3-13).

These results confirm research elsewhere showing that sediment disturbance can release pathogens that, under the right conditions, can migrate to water intakes (Burton et al., 1987; Christensen and Linden 2003). Fall test results confirm that the risk is greatest within days of the disturbance and gradually diminishes in the weeks following.

4.0 Conclusions

This study sought to answer five questions.

What is the sediment accumulation rate in the North Arm of Kalamalka Lake?
Sediment accumulated within the North Arm at an average rate of 0.353 ± 0.970 g/m²/day during the June-October trial period. There was variation between the sites and between the sample-pairs but also a clear pattern of higher accumulation within the Coldstream Creek plume paths and a reduction as distance increased from the mouth of the creek. Sediment also accumulated faster (0.780 g/m²/day) in the deeper central portion of the North Arm near the RDNO intake because of sediment focusing.

What contaminants were present in sediment that accumulated in 2018?
Numerous sediment trap metals demonstrated elevated concentrations along the Coldstream Creek plume paths, particularly at sites likely to receive creek silt and redistributed sediment from a marina or from stormwater outfalls. Chromium, copper, iron, and nickel exceeded their respective sediment guidelines in the sediment that accumulated during 2018, indicating ongoing metal inputs to Kalamalka Lake.

Sediment trap samples found elevated fecal bacteria counts near the intake location, possibly due to local waterfowl activity or re-suspension of bacteria deposited elsewhere that moved to the deep site by sediment focusing. Other sites with elevated counts were likely affected by stormwater outfalls. The presence of fecal bacteria in the sediment trap samples demonstrates that bacterial contamination is an on-going issue in the North Arm.

What is the status of possible hazardous contaminants already accumulated in the sediment?
Metals concentrations in most core samples around the perimeter of the North Arm were below guidelines, with only nickel exceeding the sediment guideline in two surface sediment samples and by only 1-3%. Distributions of numerous metals in core samples exhibited a similar pattern to the sediment traps, indicating Coldstream Creek as a key source of these sediment metals. A similar metals distribution in deep samples indicates that Coldstream Creek has been a source of sediment metals for decades.

Sediment core bacteria results were lower than the sediment trap results because *E. coli* can persist for weeks but not years in sediments. Only bacteria present in the surficial sediments can return to the water column during turbulence.

Hydrocarbon contamination and elevated metals were detected at Core Site 3. Several hazardous PAHs that are associated with stormwater exceeded guidelines for the protection of aquatic life at Site 3. Based on hydrocarbon fingerprinting, the likely source of these PAHs is stormwater from a series of nearby stormwater outfalls, while intensive power boating that occurs near that site may contribute to these sediment PAH exceedances. Overall, hydrocarbon results from this study were similar to those collected in the 2016 Kalamalka Lake boating capacity study.

What is the likely source of present and past contaminants within Kalamalka Lake sediment?
Coldstream Creek is the primary source of sediment into the North Arm of Kalamalka Lake. Sediment accumulated during the summer of 2018 contained elevated levels of numerous metals and exceeded the sediment quality guidelines for chromium, copper, iron, and nickel. Elevated *E. coli* concentrations measured near the intake may be related

to waterfowl congregation, while smaller counts near outfalls may be related to stormwater.

Based on hydrocarbon fingerprinting, the likely source of PAH exceedances found in the offshore sediment cores is stormwater, while PAH exceedances found in marina sediments is attributable to power boating (spills, 2-stroke oil, incomplete fuel combustion).

Stormwater is the main concern for the North Arm of Kalamalka Lake and Coldstream Creek is the main stormwater vector, but there are also numerous outfalls around the perimeter of the North Arm. Large power boat wakes increase the risk of returning accumulated sediment contaminants to the water column.

What is the risk to drinking water?
Sediment collected during the summer of 2018 contained elevated metals and numerous exceedances of the BC MoE sediment guidelines for the protection of aquatic life. The study results indicate that there is ongoing loading of sediment bearing heavy metals, fecal bacteria, and PAHs to the North Arm. Kalamalka Lake sediments are easily re-suspended, meaning that deposited contaminants can be returned to the water column. Regardless of the original contaminant source, boat wake and wave re-suspension of the persistent and toxic sediment contaminants found in the North Arm sediments is a concern.

The upgraded North Kalamalka Lake intake has 3.5 m of clearance from the bottom and sits at 20 m depth, and therefore has protection from re-suspended material. Activities that disturb large areas of sediment such as rototilling or wakeboard/wakesurf boats in water shallower than 4-5 m could affect the intake. Shallow private intakes are at a greater risk from sediment-borne contaminants in the North Arm of Kalamalka Lake.

5.0 Recommendations

1. Repeat the sediment trap portion of this study in near future and get *E. coli* samples speciated to determine if cattle, pets, humans or waterfowl are the contributor(s) of elevated *E. coli* detected in 2018 sediment traps.
2. Use underwater drone ROV to determine the depth to which powerboat wakes disturb sediments. This could involve watching small power craft, water ski boats starting and planning, and wakeboard/wake-ski boats under power, in 2 – 8 m (a typical operating range).
3. Consider temporarily removing the buoy marking the intake in 2019 to see if it alters waterfowl behavior and *E. coli* counts
4. Investigation the stormwater outfalls and Kalavista discharge that may be impacting Core Site 3 and 2, respectively.
5. Engage/educate homeowners that live by the lake and those who own boats.

Literature Cited

Asplund, T. R. (2000). The Effects of Motorized Watercraft on Aquatic Ecosystems. *Report Watercraft*, 1–21. https://doi.org/PUBL-SS-948-00

Beachler, M. M., & Hill, D. F. (2003). Stirring up Trouble? Resuspension of Bottom Sediments by Recreational Watercraft. *Lake and Reservoir Management*, *19*(1), 15–25. https://doi.org/10.1080/07438140309353985

Bloesch, J. (1994). A review of methods used to measure sediment resuspension. *Hydrobiologia*. https://doi.org/10.1016/0168-583X(93)95927-W

Britsh Columbia Ministry of Environment. (2004). *Criteria for Managing Contaminated Sediment in British Columbia*. Retrieved from https://www2.gov.bc.ca/assets/gov/environment/air-land-water/site-remediation/docs/policies-and-standards/sed_criteria_tech_app.pdf

Brown, B. E., Fassbender, J. L., & Winkler, R. (1992). Carbonate production and sediment transport in a marl lake of southeastern Wisconsin. *Limnology and Oceanography*, *37*(1), 184–191. https://doi.org/10.4319/lo.1992.37.1.0184

Burton, A. G., Gunnison, D., & Lanzai, G. R. (1987). Survival of Pathogenic Bacteria in Various Freshwater Sediments. *Microbiology*, *53*(4), 633–638. Retrieved from https://www.researchgate.net/publication/20047754_Survival_of_Pathogenic_Bacteria_in_Various_Fresh_Water_Sediments

Canadian Council of Ministers of the Environment. (2018). Canadian Environmental Quality Guidelines (CEQG online). Retrieved from http://st-ts.ccme.ca/

Cempel, M., & Nikel, G. (2006). Nickel: A review of its sources and environmental toxicology. *Polish Journal of Environmental Studies*, *15*(3), 375–382. https://doi.org/10.1109/TUFFC.2008.827

Christensen, J., & Linden, K. G. (2003). How particles affect UV light in the UV Disinfection of Unfiltered Drinking Water. *Journal - American Water Works Association*, *95*(4), 179–189. https://doi.org/10.1002/j.1551-8833.2003.tb10344.x

Dai, X., & Boll, J. (2006). Settling velocity of Cryptosporidium parvum and Giardia lamblia. *Water Research*, *40*(6), 1321–1325. https://doi.org/10.1016/j.watres.2006.01.027

Desloges, J. R. (1994). Varve Deposition and the Sediment Yield Record at Three Small Lakes of the Southern Canadian Cordillera. *Arctic and Alpine Research*, *26*(2), 130–140. https://doi.org/10.1080/00040851.1994.12003049

Forstner, U., & Heise, S. (2006). Assessing and managing contaminated sediments: Requirements on data quality - from molecular to river basin scale. *Croatica Chemica Acta*, *79*(1), 5–14.

Gunawardena, J., Ziyath, A. M., Egodawatta, P., Ayoko, G. A., & Goonetilleke, A. (2014). Influence of traffic characteristics on polycyclic aromatic hydrocarbon build-up on urban road surfaces. *International Journal of Environmental Science and Technology*. https://doi.org/10.1007/s13762-014-0561-8

Håkanson, L. (1977). The influence of wind, fetch, and water depth on the distribution of sediments in Lake Vänern, Sweden. *Canadian Journal of Earth Sciences*, *14*(3), 397–412. https://doi.org/10.1139/e77-040

HayCo. (2009). *Kelowna Old Floating Pontoon Sinking - Technical Memo January 12, 2009 File V13201134 and February 13, 2009 File V13201184*.

Herngren, L., Goonetilleke, A., Ayoko, G. A., & Mostert, M. M. M. (2010). Distribution of polycyclic aromatic hydrocarbons in urban stormwater in Queensland, Australia. *Environmental Pollution*. https://doi.org/10.1016/j.envpol.2010.06.015

Ishii, S., Hansen, D. L., Hicks, R. E., & Sadowsky, M. J. (2007). Beach sand and sediments are temporal sinks and sources of Escherichia coli in lake superior. *Environmental Science and Technology*. https://doi.org/10.1021/es0623156

Jang, A., Lee, S. W., Seo, Y., Kim, K. W., Kim, I. S., & Bishop, P. L. (2007). Application of mulch for treating metals in urban runoff: Batch and column test. *Water Science and Technology*. https://doi.org/10.2166/wst.2007.024

Kemp, A. L. W., Anderson, T. W., Thomas, R. L., & Mudrochova, A. (1974). Sedimentation rates and recent sediment history of Lakes Ontario, Erie and Huron. *Journal of Sedimentary Research*. https://doi.org/10.1306/74D729C3-2B21-11D7-8648000102C1865D

Kerr Wood Leidal Consulting Engineers. (2016). Kalamalka Lake Stormwater Reclamation, (January).

Kuriata-Potasznik, A., Szymczyk, S., Skwierawski, A., Glińska-Lewczuk, K., & Cymes, I. (2016). Heavy metal contamination in the surface layer of bottom sediments in a flow-through lake: A case study of Lake Symsar in Northern Poland. *Water (Switzerland)*, *8*(8). https://doi.org/10.3390/w8080358

LaLiberte, P., & Grimes, D. J. (1982). Survival of Escherichia coli in lake bottom sediment. *Applied and Environmental Microbiology*.

Larratt, H. (2001). *Lakeview Irrigation District Water Quality Report 2001 and Review of 1979 - 2001*. West Kelowna.

Larratt, H., & Self, J. (2017). *Kalamalka Lake Water Quality Study: Microflora, Water Chemistry & Thermal Profiles - 2017*.

Lima, A. L. C., Farrington, J. W., & Reddy, C. M. (2005). Combustion-derived polycyclic aromatic hydrocarbons in the environment - A review. *Environmental Forensics*, *6*(2), 109–131. https://doi.org/10.1080/15275920590952739

MacDonald, D. D., & Ingersoll, C. G. (2001a). *A Guidance Manual to Support the Assessment of Contaminated Sediments in Freshwater, Estuarine, and Marine Ecosystems in British Columbia: Volume I – An Ecosystem-Based Framework for Assessing and Managing Contaminated Sediments*. *Quality* (Vol. 3).

MacDonald, D. D., & Ingersoll, C. G. (2001b). *A Guidance Manual to Support the Assessment of Contaminated Sediments in Freshwater, Estuarine, and Marine Ecosystems in British Columbia: Volume II – Design and Implementation of Sediment Quality Investigations in Freshwater Ecosystems*. *Quality* (Vol. 3).

MacDonald, D. D., & Ingersoll, C. G. (2001c). *A Guidance Manual to Support the Assessment of Contaminated Sediments in Freshwater, Estuarine, and Marine Ecosystems in British Columbia: Volume III – Interpretation of the Results of Sediment Quality Investigations*. *Quality* (Vol. 3).

MacDonald, D. D., & Ingersoll, C. G. (2001d). *A Guidance Manual to Support the Assessment of Contaminated Sediments in Freshwater, Estuarine, and Marine Ecosystems in British Columbia: Volume IV - Supplemental Guidance on the Design and Implementation of Detailed Site Investigations in Marine and Est*. *Quality* (Vol. 3).

Mastran, T. A., Dietrich, A. M., Gallagher, D. L., & Grizzard, T. J. (1994). Distribution of polyaromatic hydrocarbons in the water column and sediments of a drinking water reservoir with respect to boating activity. *Water Research*. https://doi.org/10.1016/0043-1354(94)90051-5

Mohamad Pauzi Zakaria, †, Hideshige Takada, Shinobu Tsutsumi, Kei Ohno, Junya Yamada, Eriko Kouno, and, & Kumata, H. (2002). Distribution of Polycyclic Aromatic Hydrocarbons (PAHs) in Rivers and Estuaries in Malaysia: A Widespread Input of Petrogenic PAHs. https://doi.org/10.1021/ES011278+

Nagpal, N. K. (1993). Ambient Water Quality Criteria For Polycyclic Aromatic Hydrocarbons (PAHs). *Ministry of Environment, Lands and Parks Province of British Columbia*, (75). Retrieved from http://www.env.gov.bc.ca/wat/wq/BCguidelines/pahs/index.html

NCDEM. (1991). *Coastal Marinas: Field Survey of Contaminants and Literature Review*. Raleigh, North Carolina.

Neira, C., Cossaboon, J., Mendoza, G., Hoh, E., & Levin, L. A. (2017). Occurrence and distribution of polycyclic aromatic hydrocarbons in surface sediments of San Diego Bay marinas. *Marine Pollution Bulletin*. https://doi.org/10.1016/j.marpolbul.2016.10.009

Nelson, D. E. (2009). *Polycyclic aromatic hydrocarbons in sediments of marinas, Western Basin of Lake Erie, U.S.A.* University of Toledo. Retrieved from https://web.archive.org/web/20160102185224/utdr.utoledo.edu/cgi/viewcontent.cgi?article=2130&context=theses-dissertations

Rangsivek, R., & Jekel, M. R. (2005). Removal of dissolved metals by zero-valent iron (ZVI): Kinetics, equilibria, processes and implications for stormwater runoff treatment. *Water Research*, *39*(17), 4153–4163. https://doi.org/10.1016/j.watres.2005.07.040

Reible, D., Rao, B., Rakowska, M., Athanasiou, D., Drygiannaki, I., Bejar, M., … Pitt, R. (2018). Assessment and Management of Stormwater Impacts on Sediment Recontamination (ER-2428). Retrieved from https://clu-in.org/download/contaminantfocus/sediments/Sediment-ER-2428-FR.pdf

Rose, N. L., Morley, D., Appleby, P. G., Battarbee, R. W., Alliksaar, T., Guilizzoni, P., … Punning, J.-M. (2011). Sediment accumulation rates in European lakes since AD 1850: trends, reference conditions and exceedence. *Journal of Paleolimnology*, *45*(4), 447–468. https://doi.org/10.1007/s10933-010-9424-6

Schleppe, J., Larratt, H., & Plewes, R. (2017). *Kalamalka and Wood Lake Boat Capacity Study on Water Sources*. Retrieved from http://a100.gov.bc.ca/appsdata/acat/documents/r52567/16-1796-BoatCapacityReport-FINAL-Mar.14.2017_1499805760065_9804505186.pdf

Soil and Water Conservation Society of Metro Halifax (SWCSMH). (2016). Typical pollutants in stormwater runoff. Retrieved January 8, 2019, from http://lakes.chebucto.org/SWT/pollutants.html

Stogiannidis, E., & Laane, R. (n.d.). Source Characterization of Polycyclic Aromatic Hydrocarbons by using their Molecular Indices : An Overview of Possibilities . Reviews of Environmental Contamination and Toxicology - Supplemental Materials, 1–33. https://doi.org/10.1007/978-3-

Stogiannidis, E., & Laane, R. (2014). *Source Characterization of Polycyclic Aromatic Hydrocarbons by Using Their Molecular Indices: An Overview of Possibilities*. *Reviews of Environmental Contamination and Toxicology* (Vol. 234). https://doi.org/10.1007/978-3- which one of the stogiannidis references is correct? both look the same here

Summit Environmental Consultants. (2012). Kalamalka Lake Storm Outfall Sampling : Fall, (September).

U.S. Geological Survey. (2007). Modeling Hydrodynamics, Water Temperature and Suspended Sediment. Retrieved from http://pubs.usgs.gov/sir/2007/5008/section5.html there is also a USGS 2003 reference in text not listed here

Wetzel, R. (2001). *Limnology: lake and river ecosystems* (3rd ed.). New York: Academic Press. this is not referred to in text

Wiik, E., Bennion, H., Sayer, C. D., Davidson, T. A., Mcgowan, S., Patmore, I. R., & Clarke, S. J. (2015). Ecological sensitivity of marl lakes to nutrient enrichment: Evidence from Hawes Water, UK. *Freshwater Biology*, *60*(11), 2226–2247. https://doi.org/10.1111/fwb.12650

6.0 Appendices

6.1 Appendix 1: Data Results

Data will be provided by request of RDNO

6.2 Appendix 2: Metals Correlation Results

	Aluminum	Antimony	Arsenic	Barium	Beryllium	Bismuth	Boron	Cadmium	Calcium	Chromium	Cobalt	Copper	Iron	Lead	Lithium	Magnesium	Manganese	Molybdenum	Nickel	Phosphorus	Potassium	Selenium	Silver	Sodium	Strontium	Sulfur	Thallium	Thorium	Tin	Titanium	Uranium	Vanadium	Zinc	Zirconium
Aluminum	1	0.594027	0.640092	-0.33704	0.94998	0.815281	-0.45563	0.859899	-0.66112	0.933707	0.933333	0.952091	0.895172	0.648988	0.967807	0.775802	-0.03263	-0.26191	0.978684	-0.20806	0.934939	-0.34058	0.720703	0.178587	-0.63221	-0.48589	0.923724	0.869915	0.708073	0.782985	-0.29011	0.825152	0.849346	0.860331
Antimony	0.594027	1	0.585465	-0.38237	0.571464	0.397602	-0.31142	0.483448	-0.61943	0.58133	0.672322	0.575488	0.608945	0.412684	0.60913	0.372998	0.120059	-0.25126	0.655635	-0.34482	0.717145	-0.50199	0.10135	0.001428	-0.62541	-0.70907	0.650362	0.599756	0.420504	0.560275	-0.29849	0.669203	0.427722	0.44401
Arsenic	0.640092	0.585465	1	-0.19897	0.588688	0.693601	0.099967	0.748363	-0.39495	0.475244	0.595357	0.692389	0.500384	0.643856	0.534808	0.452275	0.61939	-0.56656	0.667015	-0.54754	0.602392	-0.23883	0.444648	0.262721	-0.40022	-0.67634	0.553945	0.414863	0.587396	0.329649	-0.64736	0.480992	0.458524	0.342936
Barium	-0.33704	-0.38237	-0.19897	1	-0.13924	-0.07321	0.782741	-0.01496	0.902739	-0.5411	-0.5841	-0.33321	-0.30563	0.271706	-0.45555	0.296501	0.390504	0.087369	-0.42973	0.390817	-0.56292	0.926454	0.113096	0.574693	0.918869	0.707146	-0.59476	-0.68509	-0.02245	-0.74941	0.392333	-0.75742	-0.06996	-0.53925
Beryllium	0.94998	0.571464	0.588688	-0.13924	1	0.846661	-0.31827	0.884393	-0.49654	0.870895	0.849446	0.905083	0.892562	0.74852	0.922782	0.856247	-0.03363	-0.19924	0.920165	-0.05951	0.84123	-0.14485	0.757698	0.321668	-0.45882	-0.36422	0.847396	0.7658	0.800877	0.68062	-0.15027	0.704643	0.904029	0.78575
Bismuth	0.815281	0.397602	0.693601	-0.07321	0.846661	1	-0.06386	0.854406	-0.36087	0.71547	0.711897	0.847645	0.73458	0.799017	0.792456	0.72472	0.175508	-0.5217	0.80576	-0.25958	0.688055	-0.06142	0.812077	0.397178	-0.32904	-0.47878	0.687644	0.551304	0.69414	0.499385	-0.36812	0.541618	0.779162	0.550591
Boron	-0.45563	-0.31142	0.099967	0.782741	-0.31827	-0.06386	1	-0.03268	0.801816	-0.65768	-0.60979	-0.33763	-0.42718	0.303793	-0.58164	-0.00267	0.671018	-0.10386	-0.46868	0.076634	-0.60727	0.764481	-0.00067	0.373397	0.795028	0.386615	-0.65427	-0.78787	-0.08544	-0.83179	0.111228	-0.7469	-0.21509	-0.7111
Cadmium	0.859899	0.483448	0.748363	-0.01496	0.884393	0.854406	-0.03268	1	-0.33719	0.695459	0.71692	0.881016	0.76878	0.879552	0.760524	0.775292	0.271316	-0.36434	0.844631	-0.18463	0.693424	-0.01021	0.869617	0.288448	-0.30973	-0.38229	0.688496	0.565991	0.714513	0.434247	-0.31579	0.515602	0.872038	0.622737
Calcium	-0.66112	-0.61943	-0.39495	0.902739	-0.49654	-0.36087	0.801816	-0.33719	1	-0.82289	-0.86333	-0.65764	-0.65621	-0.05178	-0.75807	-0.11169	0.371004	0.137851	-0.74592	0.401708	-0.85372	0.902948	-0.127	0.346557	0.997696	0.762745	-0.86497	-0.90812	-0.31636	-0.9332	0.357105	-0.95716	-0.42132	-0.79101
Chromium	0.933707	0.58133	0.475244	-0.5411	0.870895	0.71547	-0.65768	0.695459	-0.82289	1	0.980251	0.917663	0.91916	0.449686	0.983964	0.612929	-0.32221	-0.13859	0.95726	-0.18654	0.962862	-0.5374	0.561669	0.041829	-0.78991	-0.54058	0.985798	0.961669	0.621733	0.937978	-0.19235	0.940632	0.807039	0.949843
Cobalt	0.933333	0.672322	0.595357	-0.5841	0.849446	0.711897	-0.60979	0.71692	-0.86333	0.980251	1	0.927485	0.904619	0.477607	0.967102	0.5778	-0.20392	-0.23059	0.975248	-0.32435	0.990801	-0.6082	0.514664	0.012271	-0.83898	-0.65444	0.989705	0.95852	0.630247	0.92263	-0.30554	0.960079	0.771853	0.91378
Copper	0.952091	0.575488	0.692389	-0.33321	0.905083	0.847645	-0.33763	0.881016	-0.65764	0.917663	0.927485	1	0.917472	0.708236	0.931078	0.721023	-0.01419	-0.27398	0.972723	-0.22751	0.906824	-0.33352	0.721594	0.150025	-0.62612	-0.5289	0.915296	0.818254	0.720592	0.75734	-0.28709	0.814968	0.887539	0.851415
Iron	0.895172	0.608945	0.500384	-0.30563	0.892562	0.73458	-0.42718	0.76878	-0.65621	0.91916	0.904619	0.917472	1	0.64425	0.929899	0.73916	-0.24435	-0.02127	0.916395	-0.02704	0.890065	-0.35373	0.600271	0.214812	-0.61426	-0.43365	0.912912	0.851851	0.654928	0.789055	-0.0046	0.809144	0.926828	0.857172
Lead	0.648988	0.412684	0.643856	0.271706	0.74852	0.799017	0.303793	0.879552	-0.05178	0.449686	0.477607	0.708236	0.64425	1	0.550761	0.757394	0.351381	-0.33916	0.632722	-0.02988	0.465454	0.242623	0.794499	0.360548	-0.02491	-0.22786	0.440095	0.288116	0.689354	0.15534	-0.1487	0.247943	0.805218	0.336776
Lithium	0.967807	0.60913	0.534808	-0.45555	0.922782	0.792456	-0.58164	0.760524	-0.75807	0.983964	0.967102	0.931078	0.929899	0.550761	1	0.693713	-0.22024	-0.20377	0.970944	-0.17369	0.958501	-0.45351	0.638038	0.135123	-0.72511	-0.54075	0.968416	0.932521	0.651291	0.884027	-0.21631	0.898051	0.838811	0.900071
Magnesium	0.775802	0.372998	0.452275	0.296501	0.856247	0.72472	-0.00267	0.775292	-0.11169	0.612929	0.5778	0.721023	0.73916	0.757394	0.693713	1	0.133676	-0.09217	0.699277	0.072189	0.603531	0.222685	0.69596	0.624806	-0.0669	0.007624	0.56399	0.463854	0.659735	0.349634	0.090936	0.376891	0.792866	0.530342
Manganese	-0.03263	0.120059	0.61939	0.390504	-0.03363	0.175508	0.671018	0.271316	0.371004	-0.32221	-0.20392	-0.01419	-0.24435	0.351381	-0.22024	0.133676	1	-0.50502	-0.0668	-0.34957	-0.16462	0.366548	0.126091	0.376382	0.342858	-0.12113	-0.25982	-0.38327	0.052096	-0.48517	-0.46413	-0.32536	-0.15913	-0.4262
Molybdenum	-0.26191	-0.25126	-0.56656	0.087369	-0.19924	-0.5217	-0.10386	-0.36434	0.137851	-0.13859	-0.23059	-0.27398	-0.02127	-0.33916	-0.20377	-0.09217	-0.50502	1	-0.28458	0.670932	-0.23913	0.171701	-0.31743	-0.06195	0.160406	0.607064	-0.16706	-0.08771	-0.24285	-0.06148	0.854178	-0.13669	-0.044	-0.00294
Nickel	0.978684	0.655635	0.667015	-0.42973	0.920165	0.80576	-0.46868	0.844631	-0.74592	0.95726	0.975248	0.972723	0.916395	0.632722	0.970944	0.699277	-0.0668	-0.28458	1	-0.29955	0.966222	-0.44168	0.66344	0.11127	-0.71848	-0.58894	0.95526	0.895548	0.686009	0.82768	-0.31113	0.882418	0.847417	0.877405
Phosphorus	-0.20806	-0.34482	-0.54754	0.390817	-0.05951	-0.25958	0.076634	-0.18463	0.401708	-0.18654	-0.32435	-0.22751	-0.02704	-0.02988	-0.17369	0.072189	-0.34957	0.670932	-0.29955	1	-0.35001	0.505838	0.054171	0.104349	0.42931	0.66413	-0.22738	-0.19452	-0.08391	-0.21561	0.721095	-0.32238	0.114817	-0.04892
Potassium	0.934939	0.717145	0.602392	-0.56292	0.84123	0.688055	-0.60727	0.693424	-0.85372	0.962862	0.990801	0.906824	0.890065	0.465454	0.958501	0.603531	-0.16462	-0.23913	0.966222	-0.35001	1	-0.61375	0.468422	0.033214	-0.83266	-0.65234	0.977185	0.951037	0.620865	0.909306	-0.31488	0.954655	0.734099	0.883737
Selenium	-0.34058	-0.50199	-0.23883	0.926454	-0.14485	-0.06142	0.764481	-0.01021	0.902948	-0.5374	-0.6082	-0.33352	-0.35373	0.242623	-0.45351	0.222685	0.366548	0.171701	-0.44168	0.505838	-0.61375	1	0.219558	0.496069	0.920724	0.768087	-0.61178	-0.69303	-0.09442	-0.75212	0.441881	-0.76267	-0.06741	-0.52784
Silver	0.720703	0.10135	0.444648	0.113096	0.757698	0.812077	-0.00067	0.869617	-0.127	0.561669	0.514664	0.721594	0.600271	0.794499	0.638038	0.69596	0.126091	-0.31743	0.66344	0.054171	0.468422	0.219558	1	0.258193	-0.09148	-0.10642	0.496099	0.40989	0.53013	0.282042	-0.16842	0.304145	0.808902	0.51819
Sodium	0.178587	0.001428	0.262721	0.574693	0.321668	0.397178	0.373397	0.288448	0.346557	0.041829	0.012271	0.150025	0.214812	0.360548	0.135123	0.624806	0.376382	-0.06195	0.11127	0.104349	0.033214	0.496069	0.258193	1	0.382509	0.212802	0.008118	-0.1012	0.174651	-0.16062	0.219272	-0.15394	0.241494	-0.08115
Strontium	-0.63221	-0.62541	-0.40022	0.918869	-0.45882	-0.32904	0.795028	-0.30973	0.997696	-0.78991	-0.83898	-0.62612	-0.61426	-0.02491	-0.72511	-0.0669	0.342858	0.160406	-0.71848	0.42931	-0.83266	0.920724	-0.09148	0.382509	1	0.782763	-0.83897	-0.88584	-0.29382	-0.91184	0.395145	-0.94161	-0.37414	-0.75801
Sulfur	-0.48589	-0.70907	-0.67634	0.707146	-0.36422	-0.47878	0.386615	-0.38229	0.762745	-0.54058	-0.65444	-0.5289	-0.43365	-0.22786	-0.54075	0.007624	-0.12113	0.607064	-0.58894	0.66413	-0.65234	0.768087	-0.10642	0.212802	0.782763	1	-0.62807	-0.58958	-0.30771	-0.60382	0.727192	-0.69287	-0.24285	-0.40045
Thallium	0.923724	0.650362	0.553945	-0.59476	0.847396	0.687644	-0.65427	0.688496	-0.86497	0.985798	0.989705	0.915296	0.912912	0.440095	0.968416	0.56399	-0.25982	-0.16706	0.95526	-0.22738	0.977185	-0.61178	0.496099	0.008118	-0.83897	-0.62807	1	0.972242	0.642655	0.945643	-0.27223	0.964147	0.773938	0.93907
Thorium	0.869915	0.599756	0.414863	-0.68509	0.7658	0.551304	-0.78787	0.565991	-0.90812	0.961669	0.95852	0.818254	0.851851	0.288116	0.932521	0.463854	-0.38327	-0.08771	0.895548	-0.19452	0.951037	-0.69303	0.40989	-0.1012	-0.88584	-0.58958	0.972242	1	0.522963	0.969349	-0.22516	0.968478	0.689896	0.941409
Tin	0.708073	0.420504	0.587396	-0.02245	0.800877	0.69414	-0.08544	0.714513	-0.31636	0.621733	0.630247	0.720592	0.654928	0.689354	0.651291	0.659735	0.052096	-0.24285	0.686009	-0.08391	0.620865	-0.09442	0.53013	0.174651	-0.29382	-0.30771	0.642655	0.522963	1	0.492137	-0.28499	0.506032	0.697524	0.592225
Titanium	0.782985	0.560275	0.329649	-0.74941	0.68062	0.499385	-0.83179	0.434247	-0.9332	0.937978	0.92263	0.75734	0.789055	0.15534	0.884027	0.349634	-0.48517	-0.06148	0.82768	-0.21561	0.909306	-0.75212	0.282042	-0.16062	-0.91184	-0.60382	0.945643	0.969349	0.492137	1	-0.21447	0.976491	0.5912	0.914909
Uranium	-0.29011	-0.29849	-0.64736	0.392333	-0.15027	-0.36812	0.111228	-0.31579	0.357105	-0.19235	-0.30554	-0.28709	-0.0046	-0.1487	-0.21631	0.090936	-0.46413	0.854178	-0.31113	0.721095	-0.31488	0.441881	-0.16842	0.219272	0.395145	0.727192	-0.27223	-0.22516	-0.28499	-0.21447	1	-0.29556	0.045996	-0.12461
Vanadium	0.825152	0.669203	0.480992	-0.75742	0.704643	0.541618	-0.7469	0.515602	-0.95716	0.940632	0.960079	0.814968	0.809144	0.247943	0.898051	0.376891	-0.32536	-0.13669	0.882418	-0.32238	0.954655	-0.76267	0.304145	-0.15394	-0.94161	-0.69287	0.964147	0.968478	0.506032	0.976491	-0.29556	1	0.60778	0.891491
Zinc	0.849346	0.427722	0.458524	-0.06996	0.904029	0.779162	-0.21509	0.872038	-0.42132	0.807039	0.771853	0.887539	0.926828	0.805218	0.838811	0.792866	-0.15913	-0.044	0.847417	0.114817	0.734099	-0.06741	0.808902	0.241494	-0.37414	-0.24285	0.773938	0.689896	0.697524	0.5912	0.045996	0.60778	1	0.775171
Zirconium	0.860331	0.44401	0.342936	-0.53925	0.78575	0.550591	-0.7111	0.622737	-0.79101	0.949843	0.91378	0.851415	0.857172	0.336776	0.900071	0.530342	-0.4262	-0.00294	0.877405	-0.04892	0.883737	-0.52784	0.51819	-0.08115	-0.75801	-0.40045	0.93907	0.941409	0.592225	0.914909	-0.12461	0.891491	0.775171	1

6.3 Appendix 3: 2016 Boating Study Sediment Core Sites

Boating Study 2016	Latitude	Longitude	Depth (m)	Core depth (cm)	Total Metals	E. coli	Hydro-carbons
Kal S Shallow	50.116370°	-119.380150°	3	15	X	X	
Kal S Deep	50.117260°	-119.373350°	24	15	X	X	
Kal N Shallow	50.227040°	-119.266960°	14	15	X	X	
Kal N Deep	50.227220°	-119.274430°	23	15	X	X	
Kalavista Launch	50.228415°	-119.265018°	1	15	X		X

6.4 Appendix 4: 2016 Boating Study Sediment Trap Sites

Location Name 2016	Latitude	Longitude	Depth (m)
Kal S Shallow 2016	50.116370°	-119.380150°	3
Kal S Deep 2016	50.117260°	-119.373350°	24
Kal N Shallow 2016	50.227040°	-119.266960°	14
Kal N Deep 2016	50.227220°	-119.274430°	23

Typical sediment fall rates

Material	Size	Fall velocity
Inorganic		
Sand	>63 – 300 microns	> 100 m/day (15 cm/s)
Silt	4 – 63 microns	21 m/day (1-2 mm/s)
Clay	0.1 – 4 microns	1 m/day
Marl	<1.5 microns*	0.6 - <0.03 m/day
Biological		
Organic clumps	> 100 microns	< 100 m/day
Organic clumps (detritus)	< 100 microns	0.35 m/day
Large algae and diatoms	22 – 70 microns	< 50 m/day
Small algae	6 – 14 microns	<1 m/day
Lrg filament cyanobacteria	5w x 200l microns	0.1 m/day
Sm filament cyanobacteria	1w x 100l microns	>0.007 m/day
Giardia / crypto cysts	4 – 8 microns	0.02 - 0.1 m/day
Bacteria – *E. coli*	0.7 – 10 microns	>0.0035 m/day

(Dia and Boll, 2006; USGS 2003; USGS 2007; Hayco, 2009; Larratt 2010, Beachler and Hill, 2003)
* Particle size determination for Kalamalka Lake water showed marl size averaged 1.1 microns (Larratt, 2005)