An investigation of contamination in Reay Creek Pond sediments

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Executive Summary

Reay Creek pond is a small, artificial containment produced by a dam originally constructed on Reay Creek in 1935. In its early years the pond was the site of a duck farm, but over the past several decades housing developments have taken place along the creek. Victoria Airport and associated industries have also developed in the upstream drainage basin since the dam was built. This ensemble of industries has had a number of recorded spills that led directly to fish kills, and various chemical substances of industrial origin have contaminated creek sediments. Among these, cadmium (Cd), zinc (Zn) and chromium (Cr) are of great concern due to their high sediment concentrations and known toxicities. A dated sediment core collected from Reay Creek Pond shows that contaminations have occurred from several sources, but all contaminations can be assigned to locations within the Creek's drainage basin above the pond (i.e., the industrial park-airport complex). The sediment that has accumulated within the pond after its initial construction is estimated at about 2200 tonnes (dry weight) and contains approximately 70 kg of Cd, and 630 kg of Zn. This sediment reservoir, along with sediments accumulated in the creek bed, would need to be removed and confined in a permanent containment if the creek is to be remediated to point that it can safely sustain fish. Stakeholders including the residents in the Reay Creek drainage, the Victoria Airport Authority and associated industries, and the Federal, Provincial and municipal governments need to be involved in developing a remediation plan.

Introduction

Reay Creek (~ 3 km length) is located on the east side of the Saanich Peninsula near the Town of Sidney, B.C. (Figure 1a,b). Reay Creek traverses two municipalities and the Victoria International Airport before entering salt water at Bazan Bay, which borders Haro Strait. Before extensive community involvement in stream restoration and re-introduction of coho salmon (*Onchorhyncus kisutch*), the lower reach of Reay Creek was essentially a "dead stream" with considerable garbage and debris scattered throughout (T.Davis, pers comm). Coho salmon have been successfully spawning and returning to Reay Creek almost continuously since the late 1980s and wild sea-run cutthroat trout (*Onchorhyncus clarkii clarkii*) have colonized the creek as well.

The pond on Reay Creek, 255 m in length and averaging 18 m in width, was originally created for the rearing of commercial ducks through the construction of wood stave and rubble dam in 1935 (Figure 2). In the 1950s another dam was constructed 40 m downstream of the original location to increase pond capacity to support irrigation. Housing sub-divisions have been built around the pond since the early 1970s. In 1997, following a spillway failure, the dam was reconstructed under the supervision of Fisheries and Oceans Canada (FOC) and the Sidney Anglers Association (SAA).

Figure 1a. The location of Reay Creek and Reay Creek Pond on northern Saanich Peninsula.

Figure 1b. Reay Creek & Pond showing Core Locations.
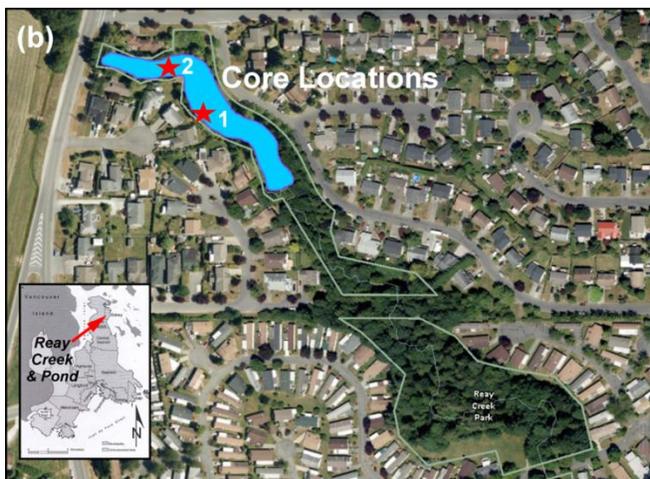
Figure 2. Plan view of Reay Creek Pond showing locations of Cores (2013), Original Dam (~1935) and transects and sampling points at which water and sediment depth were determined in 2010 (Robinson and Sarrazin, 2010).
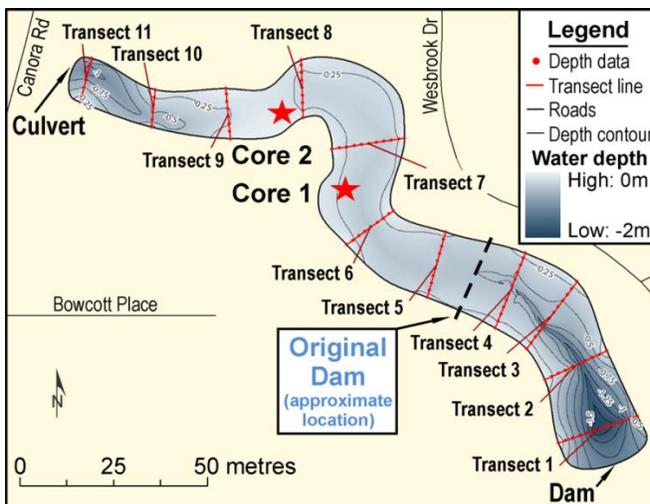
Currently the pond contains significantly more accumulated sediment (Figure 3) than overlying water, reducing potential juvenile salmonid rearing habitat in the pond by an estimated 80%. Furthermore, the accumulated sediments are nutrient rich (phosphorous/nitrogen), as evidenced by the significant blue-green algal bloom consequent to sediment disturbance in the summer of 2004 when a fallen tree was removed.

Figure 3. Histogram of uncompacted sediment depths in Reay Creek Pond as determined by Robinson and Sarrazin (2010).
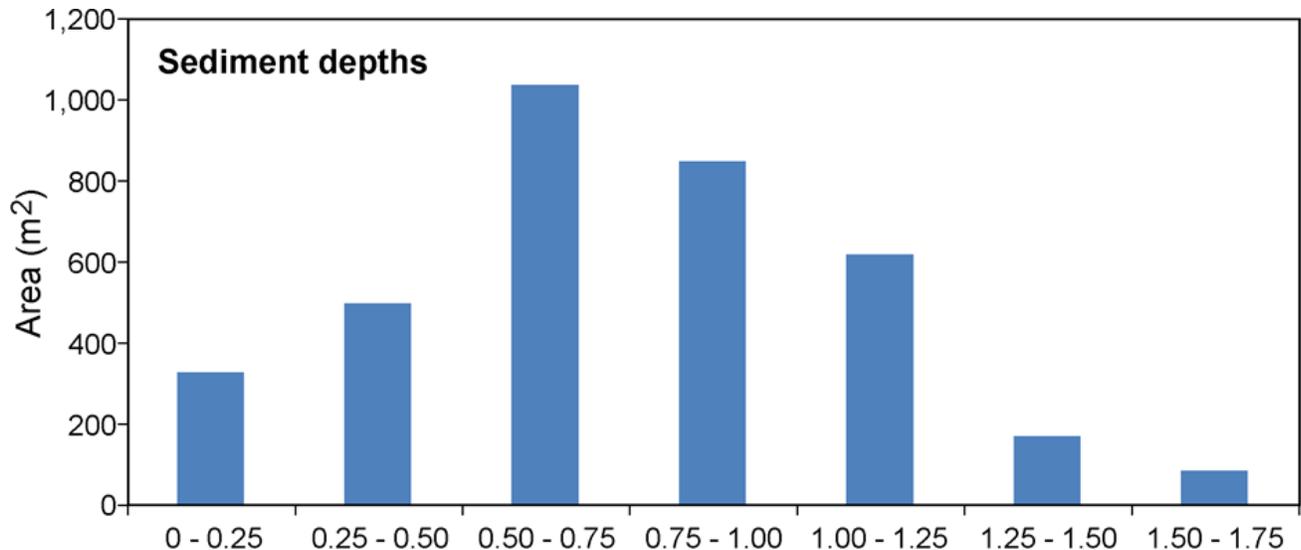
Six large mortality events of salmon and trout (1982, 1987, 1993, 1994, 2003, 2004) and three smaller ones have occurred in Reay Creek since the early 1980's with at least four of them (1982, 1987, 2003, 2004) associated with high levels of Cd originating from the Victoria International Airport (Table 1). Peninsula Streams Society (PSS) recently sponsored an investigation into the status of Reay Creek pond by two Camosun College students (Robinson and Sarrazin, 2010) in which they reported the accumulation of deep sediments (up to 1.5 m) exhibiting high concentrations of Cd in the near-surface sediments.

PSS and SAA would like to remediate the pond to increase its rearing capacity for coho salmon and sea-run cutthroat trout. The local community would like a pond that functions as fish habitat without the constant threat of blooms or downstream transport of contaminated sediments. The Town of Sidney is required to determine what, if any, financial liability there may be associated with the possibility that the pond qualifies as a contaminated site. The investigation reported here is meant to characterize the sedimentary environment of the pond in terms of accumulation history subsequent to the original damming, sediment contaminant concentrations, and the total inventory of contaminants. This information is sought to inform the development of strategies required to remediate the pond.

Table 1: Selected historical perspectives of Reay Creek Pond and of some of the contaminants found in its sediments

Year	Activity	Comments
1929	PCB used industrially	Erickson
1935	LG Thomas Sidney Duck Farm built	
1939	Vic Times reports 6,000 ducks at farm	
1939	Victoria Airport started as grass strip & Military Training	Wikipedia
1949	PFOS first produced commercially (3M)	
1950s &60s	Chromium plating plant (East Camp)	
1960s	DDT used in aerial spray for forestry	Gallager et al. (2004)
1965	PBDE produced industrially	Meunhor (2011)
1967	Anecdotal admission of toxic release by Viking Air/Airport	
1970	Viking Air established as aircraft modification/repair site	Wikipedia
1970s	Widespread use of PBDEs as flame retardant	Toxipedia
1972	DDT use banned	
1972	PCB sale for open uses ceased by Monsanto	Erickson & Kaley (2011)
1977	PCB production ceased by Monsanto	Erickson & Kaley (2011)
1977	PCB use banned in Canada	Ross et al. (2009)
1979	PCB use banned in USA (by EPA)	Erickson & Kaley (2011)
1982	Coho fry outplanted from Goldstream River	
1982	Fire at Viking Air; complete fish kill	Fire retardant and other toxics
1983	Oil spill at Airport; no fish kill	Spill Gate installed at airport
1985	Reg Kirkam moves to pond site	Small dam still prominent
1985	Fish kill (120 coho fry)	Hydrant flushing, Sidney
1987	Large fish kill	Possibly Cd?
1993	Coho/cutthroat killed over half stream length	Suspect municipal hydrant flushing
1993	Coho killed in top third, survived below mid-point	Cutthroat also killed
1994	Coho killed over the entire length	Sticklback hit hard in upper reaches (ballfield construction?)
1996	Earthen dam blowout (1 x 1.3 m)	Dam located to present situation
1997	Dam rebuilt in place with DFO Guidance	
2002	Fish kill – 18 cm cutthroat and suspect coho fry	Suspect chlorine/chloramine hydrant flushing
2003	Fish kill (Cd)	Complete, all species, Cd in fish tissues (DFO)
2004	Complete fish kill	Cd, Cr, Zn?
2004	PBDEs – production of octa and penta discontinued)	Toxipedia
2006	PBDEs – tetra through deca designated as	
2009	toxic under CEPA	
2008	PBDE production banned in Canada	
2009	PFOS included in Annex B, Stockholm Convention	Canada has proposed complete ban

Methods

The physical survey of Reay Creek Pond, conducted in June, 2010 (Robinson and Sarrazin, 2010), provided the foundation for selecting two sites within the pond to collect sediment cores (marked on Figure 2). In the 2010 survey of the pond, the depth of the water and of un-compacted sediments were measured along 11 transects at a total of 106 locations by pushing thin bamboo rods into the sediments at each location, which permitted the depth distribution of un-compacted sediment to be contoured as shown in Figure 2.

Volume and area calculations for the pond sediments

Using an enlarged version of Figure 2, we measured the total area of the pond and of the sediment thickness contours at 0.25 m intervals using a planimeter. The planimeter measurement of each closed contour area was repeated 3-4 times giving a precision of about 1-3% depending on size and shape of the area. The sum of all the individually measured sub-areas (3583 m^2) agreed within less than ±1% with the measurement of the total lake area (3612 m^2). This precision does not take into account errors inherent in the bamboo stick method of probing sediments and contouring the results. Un-compacted sediment depths were found to be mostly distributed between 0.5 m and 1.25 m (Figure 3), and the total amount of un-compacted sediment accumulated in the pond, based on the histogram in Figure 3 and the measurements of water content within the sediment core, is ~2144 tonnes (dry weight) (Table 2).

Table 2: Reay Pond area and sediment dimensions

Surface Area	3583 m^2
Total volume of accumulated sediment	3107 m^3
Total wet weight mass of sediments	4400 tonnes
Total dry weight mass of sediments	2144 tonnes
Mean depth of sediments	0.87 m

Sediment coring methodology

Two sediment cores were collected by hand on Sept. 19, 2013, at the locations marked on Figures 1a, 2 using a small boat. For each core, a plastic core liner (10 cm i.d.) with sharpened end was pressed into the sediment as far as possible. A cap was placed on the top end of the tube to provide a vacuum, the tube containing the core was retrieved from the sediment and, taking care to maintain the core in a vertical position, and the core was placed on a sectioning device. The cores were 62 cm (#1) and 38 cm (#2) in length. Both cores were sectioned at 2 cm intervals by extruding the sediment upward and subsampling the 2-cm plug, taking care to discard the outer material that had been in contact with the tube wall. Each sectional subsample was placed in a Whirlpak bag and frozen for later analysis. Core 1 was used for dating and contaminant analyses because it was longer, and appeared visually to be a better core. During sub-sectioning it was noticed that the top 24 cm of this core consisted of fairly uniform greyish black mud without any distinguishing features or obvious identifiable objects like wood or leaves (Appendix I Table 1). At about 25 cm, coarse woody material including a large wood chip was encountered, below which the sediment alternated between coarse woody material and finer mud, with a sandy layer at 39 cm, and mixed, coarse mud, and sand.

Sample Preparation and Analyses

Twelve 2 cm sectional sub-samples from Core 1 were frozen and sent to Flett Research Ltd. for ^{210}Pb counting (to date the core) and total mercury determination. The remaining sample from these sub-sections, along with the other nineteen 2 cm sectional sub-samples from Core 1 were delivered to Axys Analytical Ltd. in Sidney, B.C, to analyze for metals, organochlorine compounds (OCs) and poly-cyclic aromatic hydrocarbons (PAHs). Due to the cost of the OC and PAH determinations, we used only two pooled samples (shallow sediment, deep sediment) as indicated by colour coding showing how the sections were analyzed (Appendix I Table 1).

For all analyses reported here the complete methods (referenced in Appendix II) and the raw data themselves are available upon request as pdf/doc files or Excel files (Ian Bruce).

For metals analysis, ten samples were selected from Core 1 (Appendix I Table 1), corresponding sequentially to the list given in Maxxam ID # JF3164-JF3173 (Appendix II). These samples were analyzed for total metals using acid extraction and ICP-MS quantitation.

For analysis of polychlorinated biphenyls (PCBs), pesticides, PCN (polychorinated naphthalenes), PBDEs (polybrominated diphenyl ethers), PFC (perfluoro compounds), dioxins/furans and PAHs, two sample strata were created for each compound 0-24 cm and 24-62 cm (Appendix I Table 1).   The analyses for these compounds were undertaken by Axys Analytical Ltd. with methodology described in the report listed in Appendix II.

[210]Pb dating of sediments

The primary dating tool for the sediments was [210]Pb. Briefly, this natural radionuclide enters sediments through atmospheric deposition (excess ^{210}Pb) and through the decay of naturally occurring [226]Ra (supported ^{210}Pb) within minerals making up the sediments. To use ^{210}Pb as a dating tool, the supported [210]Pb (estimated from [226]Ra measurements) is subtracted from the total ^{210}Pb measured, to provide an excess ^{210}Pb profile. Using the decay rate of [210]Pb (1/2 life of ~22 years), the vertical profile of excess ^{210}Pb can then be used to estimate sedimentation rate and assign age to various depths in the core. Sediment mixing may complicate this estimation, requiring modeling, but in the case of the Reay Creek sediments there was no evidence of surface sediment mixing. A secondary check on sedimentation rates is often provided by [137]Cs. This element, a product of the nuclear fission of uranium, first entered atmospheric deposition in the early 1950s, when atmospheric weapons testing was initiated. The atmospheric deposition peaked in the early 1960s and then drastically declined due to test-ban treaties. A subsequent peak in ^{137}Cs deposition at our latitude occurred in 1986 due to the Chernobyl accident.

Results

Sedimentation rates and history

The ^{210}Pb data plotted as $Ln[^{210}Pb_{ex}]$ versus depth in the sediments expressed as g/cm^2 yields a

reasonably good straight line with a regression coefficient of $R^2 = 0.96$ (Figure 4). The slope of

the line implies a sedimentation rate of about 0.125 g cm^{-2} yr^{-1} (95% CI is 0.106 – 0.154 g cm^{-2} yr^{-1}). Taking into account the water content of the sediment, this translates into an average sediment velocity of ~0.32 cm yr^{-1}. Given the observations at the time of sectioning, this sedimentation rate probably applies only to the top 25 cm of the core, where the sediment appeared uniform in colour and texture. Below that is likely older material that had been disturbed during or shortly after the pond was first constructed. Accordingly, the ^{210}Pb data imply that the uniform sedimentation commenced in about ~ 1939, with a range of 1925 – 1954 possible (95% CI). These dates for the bottom of the uniform surface layer set against the known history of the pond (Table 1) suggest that the top 25 cm of sediment in the pond accumulated more or less uniformly after the duck pond was first constructed in 1935. The ^{137}Cs values are low and sporadic throughout the core, which is difficult to interpret in the context of ^{137}Cs deposition. ^{137}Cs data can be problematic for a number of reasons and we have therefore not relied on them here.

Figure 4. A plot of Ln[^{210}Pb$_{ex}$] versus sediment depth for Core 1 . Dashed line shows the line fit to the data to estimate sedimentation rates.
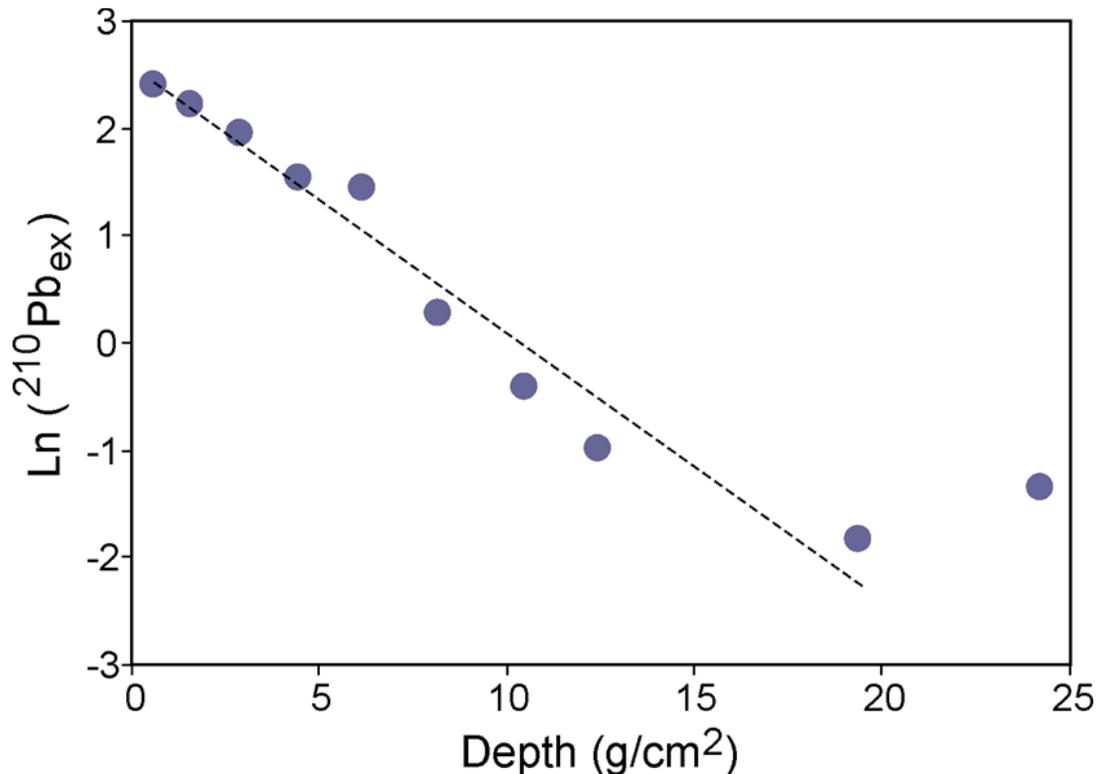
Contaminants in the pond sediments

Based on the texture and appearance of the sediments and the ^{210}Pb dating, we consider the sediments in the analyzed sediment core to consist of an overburden of fairly uniform, soft sediment that has accumulated to about 25 cm since the construction of the pond. Beneath this

are disturbed, but more compact sediment, of unknown age but presumably dating before the mid 1930s.

Metals.   We have analyzed a number of metals in the sediment cores, but in the context of contamination, toxicity and local metal sources, the relevant metals include cadmium (Cd), chromium (Cr), zinc (Zn), copper (Cu), tin (Sn), lead (Pb), mercury (Hg) and silver (Ag). A comparison of the metals data in the sediment cores with natural crustal values that would normally be expected in soils or values measured in uncontaminated horizons from BC lakes (Table 3a) shows that most of the metals exhibit contamination above expected backgrounds (e.g., Pb, Cu) , as would be expected given the pond's location near urban and light industrial developments. However, Cd and Zn both show gross contamination, with Cd clearly exceeding sediment toxicity guidelines (Table 3b). Fish kills in which Cd was implicated have been documented in 1982, 1987, 2003 and 2004. However, these incidents seem not to explain all of the Cd contamination given that it extends into times well before 1982.

Table 3a Metals data for Core 1 (all units in µg/g)

Element µg/g	Crustal Value[1,2]	BC Lakes[3]	Reay Pond 0 to 24 cm Average	SD (n=6)	Reay Pond 24-62 cm Average	SD (n=4)
Pb	12.5 – 15	8 – 30	78.6	10.1	37	19.5
Cd	0.1 – 0.2		27.9	16.5	34.2	14.6
Cu	25 – 55	35 – 105	98.2	18.8	43.7	10.4
Zn	65 – 70	85 – 180	741	154	234	97
Hg	0.08	0.012 – 0.35	0.06	0.006	0.066	0.011
Cr	100 – 200	80 – 150	148	46	190	37
Ag	0.07 – 0.1		0.4	0.04	0.2	0.1
Sn	2		1.8	0.3	1.1	0.2
As	1.8		5.4	0.14	6.2	2.3

[1] Taylor, 1964. [2]Turekian and Wedepohl, 1961. [3]Gallagher et al., 2004.

Table 3b Reay Creek Pond sediment averages for metals and sediment guideline values (all units are µg/g)

Element	Sample Concentration Mean	SD (n=10)	BC FW Sediment[1] SedQCscs[3]	SedQtcs[3]	CCME FW Sediment[2] ISQC[4]	PEL[5]
arsenic	5.7	1.5	11	20	5.9	17
cadmium	30.4	15.5	2.2	4.2	0.6	3.5
chromium	164.8	44.6	56	110	37.3	90
copper	76.4	29.4	120	240	35.7	197
lead	62	26.5	57	110	35	91.3
mercury	0.043	0.008	0.3	0.58	0.17	0.486
zinc	538	271.6	200	380	123	315

[1]Criteria for Managing Contaminated Sediments in British Columbia- Technical Appendix;
[2]CCME Fresh Water Sediment Guidelines; [3]Sediment Quality Criteria: scs – sensitive contaminated sites; tcs – typical contaminated sites; [4]Interim Sediment Quality Guideline; [5]Probable Effects Limit

Plots of the variation in metal concentrations with depth/age in sediments (Figure 5) give an indication of the time course of contamination. Together with an analysis of multiple correlations (Table 4), the profiles shown in Figure 5 reveal that metal contamination has likely occurred from three different sources. First, Cd and Cr profiles show significant similarity (R=0.84, p=0.0025),and have the deepest (longest) record of contamination. For both of these metals, the near-surface sediments (post 1964) tend to be lower than deep sediments, but in the case of Cd the values indicate gross contamination right up to the sediment surface. That is, sediments accumulating today still have Cd contents that exceed toxicity limits given in Table 3b, which suggests that suspended sediment transported by Reay Creek above the pond remains unacceptably high in Cd. Cd and Cr have contaminated the sediments in the ratio of 0.28:1 (Cd:Cr), and that contamination appears to have commenced very early in the pond's history. The second grouping of metals includes Zn, Cu and Sn. All three of these metals exhibit low values within normal crustal ranges in the deep sediments. These concentrations become markedly higher after about 1940 and have remained at more or less constant concentrations near the surface after about 1990. The correlation between Zn and Cu is particularly strong (R=0.99, p=0.0003), but correlations between these two metals (Zn, Cu) and Sn are also significant (R=0.90, p=0.0005). The contamination by these three metals is in the ratio of 563:63:1 (Zn:Cu:Sn). The final pairing, between Pb and Ag (R=0.92, p=0.002), shows background crustal values deep in the core, with contamination commencing in about 1940 where it rises sharply until about 1960 and thereafter has very gradually declined. The ratio for this contaminant pair is 175:1 (Pb:Ag). Hg, another metal that frequently poses toxic risks, appears never to have contaminated the Reay Creek Pond sediments (Table 3a) and manifests no vertical trends in the sediments.

Figure 5. Plots of selected metal concentrations as a function of depth in the sediments.
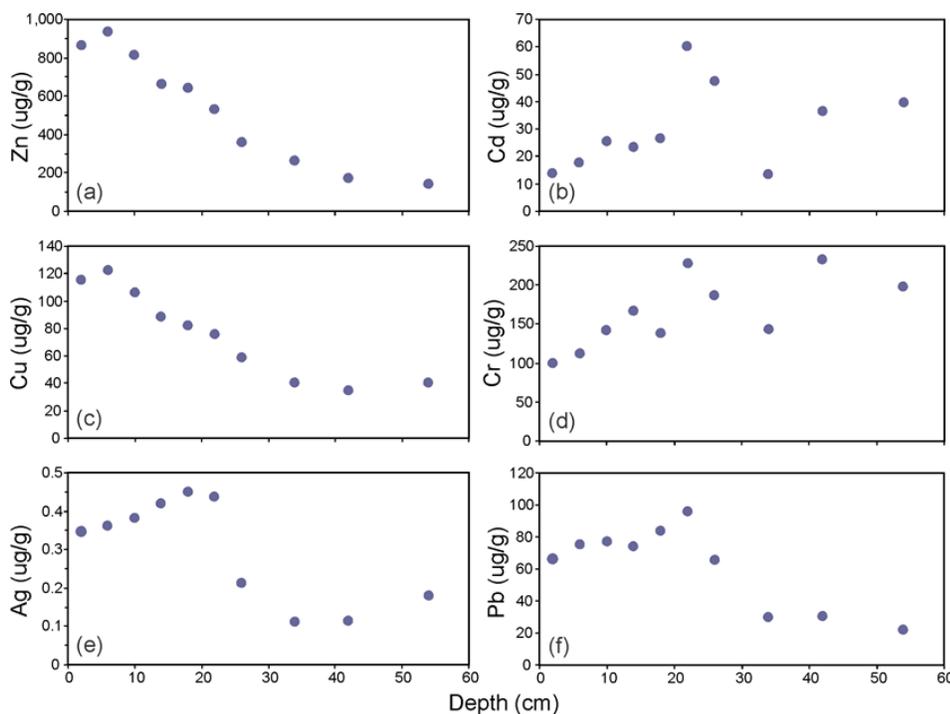
Table 4. Multiple correlations for the metals data

	Cd	Cr	Cu	Pb	Ag	Sn	Zn	As
Cd	1							
Cr	**0.84**	1						
Cu	-0.40	-0.71	1					
Pb	-0.16	-0.23	0.72	1				
Ag	0.02	-0.32	0.77	**0.92**	1			
Sn	-0.34	-0.55	**0.91**	0.61	0.68	1		
Zn	-0.43	-0.73	**0.99**	0.75	0.78	**0.90**	1	
As	0.14	0.20	-0.31	-0.51	-0.24	-0.27	-0.39	1

PCBs. Two samples were analyzed, one on a pooled sample of sediment from 0 – 24 cm in the core, the second on a pooled sample from 24 – 62 cm in the core.   Based on the ^{210}Pb dating, the latter pooled sample would represent early material predating the pond construction and the former pooled sample the more recent material accumulated within the pond. The total PCB (∑PCBs) concentration, calculated by summing the congener data, was 95 ng/g and 213 ng/g for the top and bottom sediments respectively (Table 5). These concentration levels indicate contamination has been occurring in Reay Creek for a long time, which is not surprising given the

Table 5. Summary of concentration data from pooled sediments (upper and lower core segments) together with some guideline values for sediments

Sediment Depth (cm)	∑PCBs ng/g	∑PBDEs ng/g	∑PAHs ng/g	∑DDTs ng/g	∑Chlordanes ng/g	∑PFOS ng/g
0 – 24	95	52	18,000	9	0.7	5.8
24 – 62	213	<1	<1,000	48	0.6	0.8
SEQCscs[1]	170		10,000	3	5.5	
ISQG[2]	34.1		n/a	n/a	4.5	
PEL[3]	277		n/a	n/a	8.87	

[1]Sediment Quality Criteria – sensitive contaminated sites, Criteria for Managing Contaminated sediments in British Columbia, Technical Appendix
[2]Interim Sediment Quality Guideline, CCME FW Sediment Guidelines
[3]Probable Effects Limit, CCME FW Sediment Guidelines

multiple distributed sources of PCBs that include paint, plasticizers, electronics, lights, oils, thermal transfer fluids, hydraulic fluids, carbon copy paper, and others. Greater contamination
deeper in the sediments would also be consistent with the known history of use, which commenced in 1929 and was curtailed in the early 1970s when environmental and health risks of PCBs became widely recognized (Table 2). For comparison, ∑PCBs measured in sediments of the Strait of Georgia near municipal outfalls show contamination levels that are generally <10 ng/g dry weight (Johannessen et al., 2008). However, the sites in the Strait of Georgia likely experience greater dilution of PCBs due to the nearby supply of inorganic sediment from the Fraser River, which also helps to bury the PCBs. An examination of the histogram of PCBs according to chlorine substitution (Figure 6) shows the deeper sediments to be 'lighter' (containing less chlorine) than the surface sediments (ignoring for the moment the large peak for deca-PCB) with the largest peak seen at penta CB compared to hexa and hepta CB for the top-layer sediments. Both samples,

however, contain relatively heavy PCB (compare with PCB formulation 1254 (Figure 6) or the average PCB Cl-substitution histogram for Strait of Georgia sediments (see Figure 9 in Johannessen et al., 2008), indicating that the source of PCBs in Reay Creek sediments is probably local rather than distilled PCB via long-range transport.   The large peak for deca-PCB in the deep sediment is clearly anomalous and cannot be explained by any of the traditional PCB formulations used such as 1254. Nor could such a heavy PCB be explained by long-range transport given its low volatility. Deca-PCB (also known as deca wax) was used in a relatively pure form for investment casting (Erickson and Kaley, 2011). Specifically, this process is used to produce precision-cast metal parts and shapes for the aircraft and other machinery manufacturing industries. Thus it seems likely that deca-wax was used locally (upper Reay Creek drainage) for aircraft-parts production in the 1950s-60s. Fortunately, this heavy PCB is not particularly toxic given that it is not taken up by biota very easily.

Figure 6. A histogram of PCB congener data organized by chlorine number for the pooled sediment samples (0-24 cm and 24-62 cm) and the commercial PCB mixture "1254".
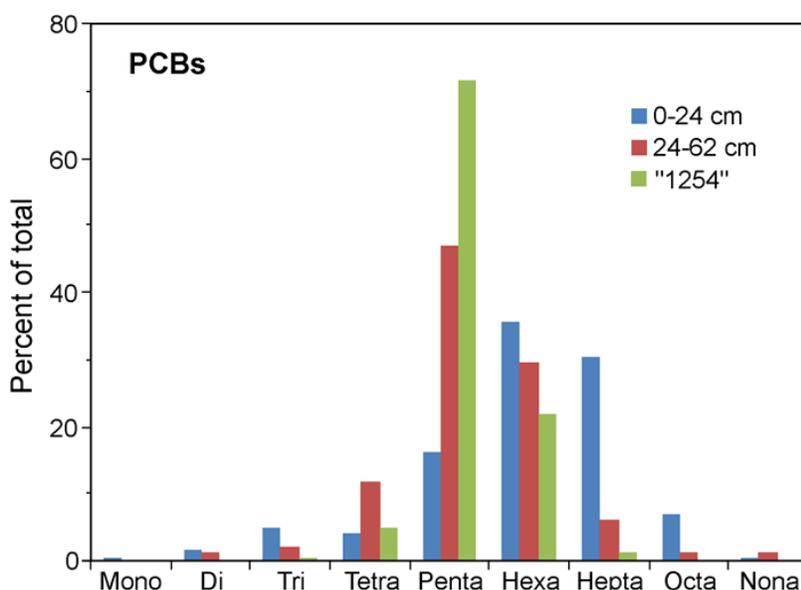
PBDEs. Like PCBs, these compounds have enjoyed wide use as flame retardants in fabrics, electronics and flame retardant fluids used to suppress fires. An important difference between these brominated compounds and PCBs is that their whole-scale use did not commence until much later, in the 1980s. Concerns about their environmental and health effects, similar to the concerns over PCBs, have led to their partial or complete banning in the 2000s (Ross et al., 2009). For the Reay Creek Pond sediments, ∑PBDEs concentrations were found to be 52 ng/g in the upper sediments and <1 ng/g in the deep sediments. Again, this depth distribution is reasonable given the much later entry of PBDEs into widespread use than the PCBs. An examination of the congener profile (Figure 7) shows that congeners 47, 99 and, especially 209, provide most of the ∑PBDE burden, which is not surprising as these are 'the usual suspects' in formulations of PBDEs some of which include mostly BDE 209 (Ross et al., 2009; De Wit, 2002). Locally, an important source of PBDEs has been marine outfalls (Dinn et al., 2012a,b), likely because they dispose of

domestic wastewater containing household dust from fabrics like curtains and carpets, which frequently contain fire retardants. Near outfalls in the Strait of Georgia and Juan de Fuca, PBDE contamination of sediments, accordingly, attains concentrations of up to 20 ng/g. Thus, the upper sediments of Reay Creek Pond can be considered contaminated at relatively high levels, perhaps not surprising given the urban setting together with the known use of flame retardants to suppress a fire at Viking Air in 1982 in the drainage basin above the pond, and possibly other applications associated with the airport.

Figure 7. A bar diagram showing PBDE congener concentrations for the pooled sediment samples (0-24 cm and 24-62 cm).

PAHs. Aromatic hydrocarbons have long been of environmental concern due to their toxicities and carcinogenicities. In the environment, these compounds come predominantly from two sources – combustion (e.g., burning of biomass, or burning of liquid and solid fuels) and petrogenic (e.g., formation in sediment and rock containing organic matter, usually involving long periods of time and elevated temperatures). Each of these processes tends to produce different compound compositions, which can be used as a way to infer source (e.g., Yunker et al., 2002).   For the Reay Creek Pond sediments, the pooled sample from the top of the core had a ∑PAH of 18 µg/g compared to <1 µg/g in the deep sediments (in this case, ∑PAH refers to the sum of 14 parent PAHs included in list used by the United States' Environmental Protection Agency (USEPA) (and see Figure 8; Table 5). The source of these PAHs is probably multifold, including nearby combustion, small oil spills, crank-case oil/street runoff, and local use of creosote as a wood preservative. For comparison, a survey of lakes in the Fraser River drainage basin, some of which had adjacent roads and industry, and the Strait of Georgia, yielded ∑PAH concentrations usually much less than 1 µg/g (Yunker and Macdonald, 2003).

Figure 8. PAH concentrations for the14 parent PAHs measured in the pooled sediment samples (0-24 cm and 24-62 cm).

Pesticides. DDT is, perhaps, the classic pesticide that precipitated awareness of the danger of persistent, bioaccumulating, toxic (PBT) substances on non-target species when released broadly to the environment. DDT came into prominent use during and after the Second World War, but was banned in the USA for agricultural use in 1972, and later banned worldwide for such use under the Stockholm Convention in 2004 (Table 2). DDT was used in BC during the 1950s and 60s, both locally and by aerial spraying (e.g., Macdonald et al., 2000). The family of DDT compounds found in the environment consists of DDT itself, DDE (produced by metabolism under oxic conditions) and DDD (produced under anoxic conditions in sediments). Accordingly, the distribution of DDT/DDE/DDD compounds is often used to infer how fresh/recent the DDT is, and how the weathering of DDT has occurred after release. For Reay Creek Pond, ∑DDT concentrations were determined at 8.7 ng/g and 48 ng/g for top and bottom segments of the sediment core (Table 4). Higher concentrations in the older material at the bottom of the core are not surprising given the prevalent and sometimes casual use, commercially and privately, back in the 1940s-50s compared to post-1970. An interesting feature of the DDT profiles (Figure 9) is that the deep sediment contains DDD >> DDE > DDT, suggesting that fairly fresh DDT originally entered those sediments, but that much of the DDT then metabolized to DDD within the sediments after burial. Surface sediments contain amounts in the order DDD ≈ DDE > DDT suggesting that both oxic and anoxic metabolism have played a role in weathering the DDT before and/or after burial. Very low, but detectable, concentrations of other pesticides like the chlordanes, HCHs, and mirex were also found, but toxaphene was not detected.

Figure 9. DDT compounds measured in the pooled sediment samples (0-24 cm and 24-62 cm).
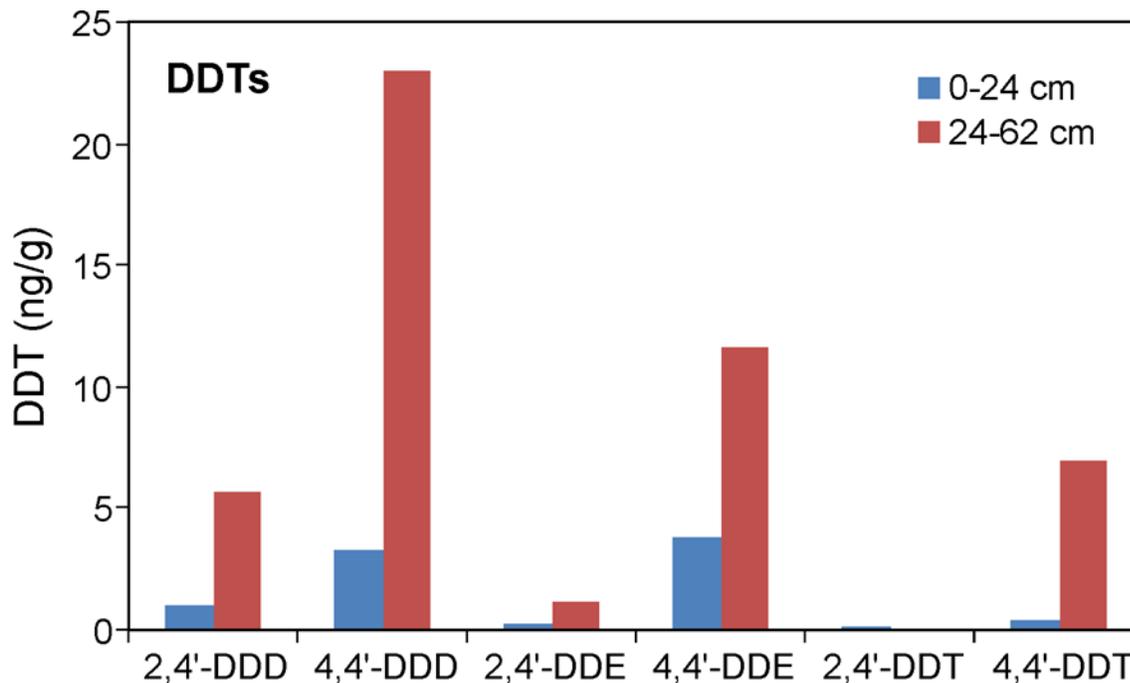
PFOS (perfluorooctanesulfonic acid or perfluorooctane sulfonate) compounds have been used widely as fluorosurfactants to protect fabrics from staining (e.g., Scotchgard). These compounds have also been used in metal plating and fire-fighting foams. First produced in 1949 (Table 2), they began to be recognized for their PBT risks in the environment in the late 1960s and were phased out of use in the USA after about 2000. These compounds were added to the Stockholm Convention Annex B in 2009. Given that history, it is not surprising that PFOS compounds are more prevalent in the top of the sediments.

Discussion

In addition to a number of physical alterations, including the removal of overburden to produce the pond in 1935, Reay Creek Pond has been the recipient of numerous industrial chemical contaminants. Many of these contaminants attain relatively high concentrations including in particular Cd and Zn, PCBs/PBDEs and parent PAHs. The contaminating sources are likely mixed, and have certainly operated on pond sediments over different periods of time. At about the time the pond was built, it is likely that it was already the recipient of Cd, PCB and DDT contamination. After construction of the pond, Zn became a dominant metal contaminant, and both PAHs and PBDEs increased to high concentration in upper parts of the sediments. In the case of PAHs, the probable effects levels occur for some of the parent PAHs at ≤1 µg/g concentrations (Yunker and Macdonald, 1995; Long and Morgan, 1990), which is well below the ∑PAHs (18 µg/g). For metals, Table 3b shows that As, Cu and Hg are not of great concern. Pb exceeds some of the quality guidelines but meets others. The prominent concern for Reay Creek, however, is Cd, which grossly exceeds all sediment guidelines. Zn and Cr also exceed guidelines.

Based on the concentration data for contaminants (Tables 3) and the estimates of sediment burden (top and bottom) presently contained in Reay Creek Pond (Table 1) we have estimated the total inventories of contaminants held in the pond sediments (background values have been subtracted from the calculation for the metals) and summarize these in Tables 6a,b. Here, we have assumed that the analyzed sediment core fairly represents the whole sediment burden accumulated within the pond. To gain better confidence in these values it would be necessary to conduct further analyses from other locations in the pond using Figure 2 to select locations containing reasonable accumulations of sediment.

Table 6a Burden of contaminants metals and ΣPAHs in Reay Pond sediments (kg)

Depth in Sediments (cm)	Cd	Pb	Cu	Zn	ΣPAHs
Top 24 cm	24	41	54	512	18
Deeper sediments	44	9	3	122	1
Total	68	50	57	634	19

Table 6b Burden of organochlorine contaminants in Reay Pond sediments (g)

Depth in Sediments (cm)	ΣPBDEs	ΣPCBs	ΣDDTs	ΣPFOS
Top 24 cm	44	81	7	5
Deeper sediments	1	276	63	1
Total	45	357	70	6

Recommendations

- A multi-stakeholder process should be initiated to determine the extent of contamination for the metals of greatest concern (Cd, Zn, Cr) including sediments from the creek bed upstream and downstream of the pond. Notices should also be posted informing the public of the concerns.

- Representatives of all levels of government, local residents and other agencies operating within the drainage basin (e.g., Victoria Airport Authority) should be brought together (e.g., Reay Creek Roundtable) to develop jointly strategies to complete the Reay Creek contamination assessment and recommend a remediation process. These tasks are urgent.

- The Reay Creek Roundtable should develop solutions to the problem of Reay Creek heavy metal contamination that will protect aquatic life, the health of those living nearby and their property values. Stormwater quality and quantity in Reay Creek watershed need to be brought under control as part of the long-term solution.

- Effectively, the only way to remove the threat of toxic metal release from the Reay Creek Pond sediments would be to remove them and place them into permanent containment, which would also secure the other contaminants. Additionally, strategies for removing any contaminated sediments located downstream of the dam in both the Town of Sidney and the District of North Saanich need to be developed.

- Given that the contamination, which originated in the upstream industrial setting, is located in a residential neighborhood, local citizens must be engaged in the process of investigating and remediating the contamination.

- As long as these sediments remain within the pond, activities that would disturb them should be avoided to prevent migration of contaminants and greater risk of exposure to aquatic biota.

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Appendix I

Appendix I Table 1								
Reay Creek Pond Sediment Core 1 - September 19th 2013								
Observations During Sectioning				**Analysis Sub-Section Groupings**				
Depth (cm)	**Comments**	**^{210}Pb**	**Hg (Flynn)**	**Metals**	**PCBs**	**PCN/PBDE/PFOS**	**Dioxin/Furans**	**PAH**
0 - 2	0-24 greyish black mud, uniform							
2 - 4	0-24 greyish black mud, uniform	x	x					
4 - 6	0-24 greyish black mud, uniform							
6 - 8	0-24 greyish black mud, uniform	x	x					
8 - 10	0-24 greyish black mud, uniform							
10 - 12	0-24 greyish black mud, uniform	x	x					
12 - 14	0-24 greyish black mud, uniform							
14 - 16	0-24 greyish black mud, uniform	x	x					
16 - 18	0-24 greyish black mud, uniform							
18 - 20	0-24 greyish black mud, uniform	x	x					
20 - 22	0-24 greyish black mud, uniform							
22 - 24	0-24 greyish black mud, uniform	x	x					
24 - 26	begin coarse woody material, big wood chip							
26 - 28	sediment going back to finer material	x	x					
28 - 30	fine but moving back to coarse, woody chips							
30 - 32	fine but moving back to coarse, woody chips,	x	x					
32 - 34	90% pure wood chips and bits							
34 - 36								
36 - 38								
38 - 40	quite sandy							
40 - 42	less wood, more sand							
42 - 44	more fine material, aluminum foil	x	x					
44 - 46	creosote? Separate sample taken.							
46 - 48	less creosote smell, almost no chips, less sand, drier material, small white globular flecks (separate sample)							
48 - 50	sandy mud, no smell, much like top of core	x	x					
50 - 52	oil smell and sheen, a bit sandy/gritty							
52 - 54	more oily material							
54 - 56	less oily, some grit, some woody bits, but mostly dirt							
56 - 58	no smell, more dirt, less sawdust, dry and firm	x	x					
58 - 60								
60 - 62		x	x					
62 - 64	Bottom of core							

Appendix II

Analytical Methodology Sources (available on request along with Excel spreadsheets of the data (Ian Bruce))

Radionuclides (^{210}Pb, ^{226}Ra, ^{137}Cs): Summary of Pb-210, Ra-226 and Cs-137 Methods as performed at Flett Research Ltd, Winnipeg, Canada Last Modified by X. Hu on March 26, 2014

Metals:

PCBs: as described in Summary of AXYS Method MLA-010 Rev 11 Ver 03: Analytical method for the determination of 209 PCB congeners by EPA Method 1668A1, EPA METHOD 1668C2 or EPA method CBC01.23.

PBDEs: as described in Summary of AXYS method MLA-033 Rev. 06 Ver. 02: Analytical method for the determination of brominated diphenyl ethers (BDE) and other brominated flame retardants (BFR).

PAHs: as described in Summary of AXYS Method MLA-021 Rev. 12 Ver. 03: Analytical method for the determination of polycyclic aromatic hydrocarbons (PAH), alkylated polycyclic aromatic hydrocarbons, and alkanes.

Pesticides: Summary of AXYS Method MLA-028 Rev 06 Ver 07: Analytical procedures for organochlorine pesticides by isotope dilution HRGC/HRMS.

PFOS: Summary of AXYS Method MLA-041 Rev. 09 Ver. 03: Analytical Procedure for the Analysis of Perfluorinated Organic Compounds in Solid Samples by LC-MS/MS.