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Remediation of PCB contaminated soils in the Canadian Arctic: Excavation and surface PRB technology

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ABSTRACT

The site BAF-5 is located on the summit of Resolution Island, Nunavut, just southeast of Baffin Island at 61° 35′N and 60° 40′W. The site was part of a North American military defense system established in the 1950s that became heavily contaminated with PCBs during and subsequent, its operational years. Remediation through excavation of the PCB contaminated soil at Resolution Island began in 1999 and at its completion in 2006 approximately 5 tonnes of pure PCBs in approximately 20,000 m^3 of soil were remediated. Remediation strategies were based on both quantity of soil and level of contamination in the soil. Excavation removed 96% of the PCB contaminated soil on site. In 2003, a surface funnel-and-gate permeable reactive barrier was design and constructed to treat the remaining contamination left in rock crevices and inaccessible areas of the site. Excavation had destabilized contaminated soil in the area, enabling contaminant migration through erosion and runoff pathways. The barrier was designed to maximize sedimentation through settling ponds. This bulk removal enabled the treatment of highly contaminated fines and water through a permeable gate. The increased sediment loading during excavation required both modifications to the funnel and a shift to a more permeable, granular system. Granulated activated charcoal was chosen for its ability to both act as a particle retention filter and adsorptive filter. The reduction in mass of PCB and volume of soils trapped by the funnel of the barrier indicate that soils are re-stabilizing. In 2007, nonwoven geotextiles were re-introduced back into the filtration system as fine filtering could be achieved without clogging. Monitoring sites downstream indicate that the barrier system is effective. This paper describes the field progress of PCB remediation at Resolution Island.

1. Introduction

1.1. Background

Localized PCB contamination in the Arctic has been documented at the Distant Early Warning (DEW Line) sites, a string of 63 military radar stations that were operated across Alaska, northern Canada and Greenland during the 1950s and early 1960 (Bright et al., 1995a,b; Stow et al., 2005).

The radar station on Resolution Island, referred to herein as BAF-5, is located at the southeastern tip of Baffin Island approximately 310 km southeast of Iqaluit and at the end of Frobisher Bay (61° 35′N and 60° 40′W, Fig. 1). The main station site is situated on a summit 360 m above sea level on Cape Warwick at the northeastern end of the island overlooking Brewer Bay. Approaches to the island are by sea at Brewer Bay, and by air using a runway located northwest of the summit.

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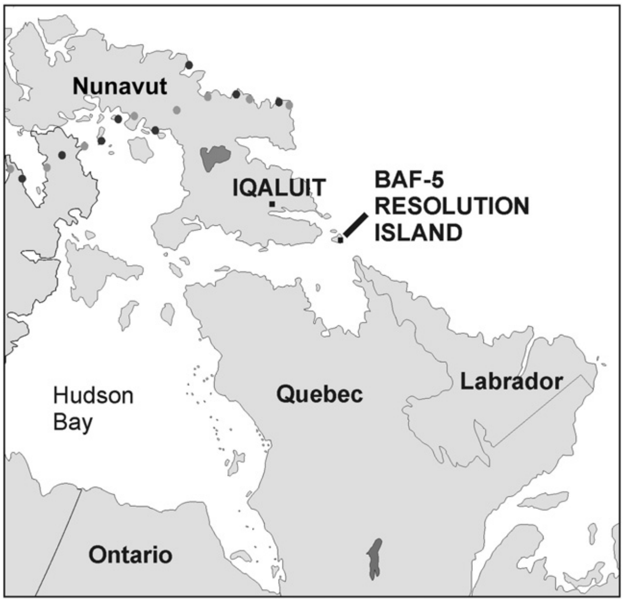

Fig. 1 – Map showing location of BAF-5, Nunavut.

After site abandonment, approximately 8000 kg of pure PCBs (Aroclor 1260) remained on BAF-5, with an estimated 4000 kg (predominately in oil) removed in 1999 (Poland et al., 2001). The remaining 4000 kg of PCBs was distributed in over 20,000 m^3 of soil. The field season at BAF-5 is short and site challenges are amplified by limited access and harsh climatic conditions. Remediation of the PCB contaminated soil under these conditions required the development of a unique cleanup strategy and a novel remediation technology.

Disposal and excavation techniques were adapted to accommodate three different contamination levels that corresponded to three PCB concentration ranges. Different, nonconventional excavation protocols were required for areas which were difficult to access. Several areas were heavily contaminated with PCBs. The area most heavily contaminated with PCBs surrounded the troposcatter dishes and buildings. At Resolution Island, stores of PCB containing oil and equipment were left unattended for several decades during which containers and equipment failed and spilled their contents (Reimer et al., 1993; Poland et al., 2001). Much of the PCB contamination migrated through a drainage pathway that was also used to flush sewage from the camp.

PCBs are known to bioacculumate and biomagnify in fatty tissues (Muir et al., 1999) and are suspected carcinogens (Silberhorn et al., 1990). In the Arctic, there is a narrow food web and Northern inhabitants are susceptible to exposure to contaminants such as PCBs via consumption of local foods (Van Oostdam et al., 1999).

The majority of these PCBs are transported via water runoff, which then enters the surrounding Arctic Ocean ecosystem (Poland et al., 2001). Source removal by soil excavation is often used for remediation of these sites. Unfortunately, much PCB contamination can be left behind during this process in the form of loosened, mobile soils.

The difficult terrain and the fractured bedrock of the site ensured that some PCB contaminated soil would remain on site after the cleanup was complete. Surface funnel-and-gate permeable reactive barriers were designed and constructed on site to mitigate the PCB migration via runoff into the Arctic ecosystem as part of a long-term remediation plan. The localized nature, associated site infrastructure and concentrated nature of the contamination at BAF-5 supported the targeted treatment area of drainage pathways (Poland et al., 2001; Stow et al., 2005).

Three areas were targeted for PCB remediation and eventual barrier construction; the S1/S4 valley, the S1/S4 Beach and the Furniture Dump (Fig. 2). The initial barrier was installed in 2003 and since then, modifications have been added to improve the performance of the barrier. Two additional permanent barriers have since been constructed and monitored. The objective of this paper is to describe the development and implementation of the cleanup strategy, the excavation and disposal of the PCB contaminated soils, and the design, construction and performance of a surface permeable reactive barrier system. This paper will show how permeable reactive barrier design can be modified to remediate surface conditions in cold regions. The application of PRBs has been investigated in cold regions such as the Arctic (Poland et al., 2001; Lindsay and Coulter, 2003) and the Antarctic (Snape et al., 2001; Woinarski et al., 2003; Gore et al., 2006; Woinarski et al., 2006). Only the barriers installed on BAF-5 however are solely surface barriers for PCB remediation. This paper is a substantially expanded version of the conference paper by Kalinovich et al. (2006).

1.2. *Cleanup criteria*

The Canadian Environmental Protection Act (CEPA) regulates the removal and destruction of PCB contaminated materials at concentrations greater than 50 ppm (CEPA, 1999). In this paper, soils containing over 50 ppm PCBs are referred to as CEPA soils. For the DEW Line sites, the CCME (Canadian Council of the Ministers of the Environment) guidelines were

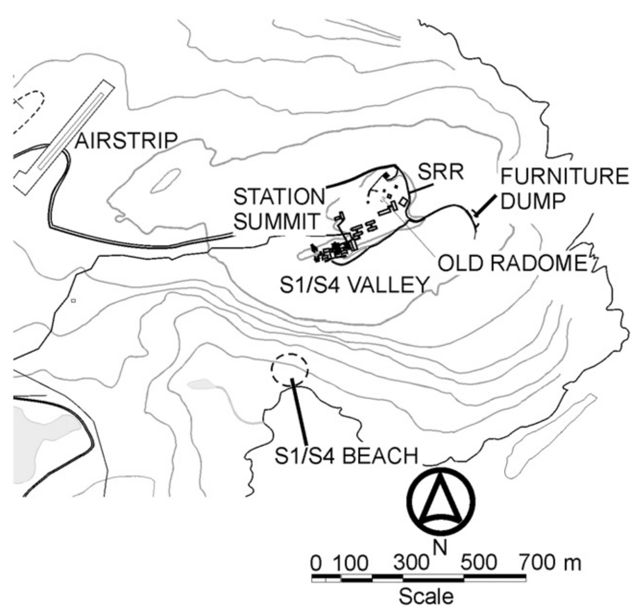

Fig. 2 – Map showing areas of contamination: S1/S4 Valley and Beach, Furniture Dump.

not available in 1991 and therefore tiers of contamination, known as the DEW Line Cleanup Criteria (DCC), were developed based on uptake of contaminants by plants as well as reference to guidelines from other countries (Reimer et al., 1993; Poland et al., 2001). The DCC were developed as part of the larger DEW Line Clean Up (DLCU) Protocol, which defined what would happen to the soils contaminated at various levels as well as what should be done to remediate old landfills, dumps, abandoned buildings, physical debris and barrels (Poland and Riddle, 2003; INAC, 2005). Two DCC levels were developed, Tier I and Tier II. For lead and PCBs, a lower level, Tier I, was instituted to take account of the mobility of these two contaminants in the Arctic, which, by 1991, had been detected at a distance of several miles from point sources (Poland et al., 2001). The "halo effect" of PCBs, from atmospheric distribution, is well-documented (Bright et al., 1995a,b; Dushenko et al., 1996; Macdonald et al., 2000; Pier et al., 2003; Stow et al., 2005). Tier II accounted for the material greater than Tier I and less than CEPA. The three soil PCB concentration ranges, CEPA, Tier II and Tier I (Table 1) correspond to three different action levels on site, based on the DLCU protocol.

2. Methods

2.1. *Delineation and grid maps*

Soil contamination levels were evaluated in the assessment phases (Poland et al., 2001). To facilitate remediation, areas were sectioned off into 20 m×20 m grids using a Ashtech-Reliance differential global positioning system (DGPS) and Autocad Map 2000. The grids were established on site by using waypoint navigation and corners of the grids were clearly marked on site with flags and spray paint and re-established at the beginning of each field season. Areas of contamination, CEPA, Tier II and Tier I were delineated on site using a coloured rope system and spray paint. Additional samples were taken as required to clearly establish contaminated areas.

2.2. *Sampling and analysis*

All soil samples were taken from depths of 0 to 10 cm where possible and placed in Whirlpak bags. Point samples were taken to confirm Tier I, Tier II and CEPA areas as necessary. Composite samples (soil samples from 3–5 locations within the area in question) were employed during excavation for confirmatory testing. The maximum area for composite samples was 5 m by 5 m but smaller areas were sampled as necessitated by topography.

Table 1 – Cleanup criteria and the DLCU protocol (Poland et al., 2001; INAC, 2005)

Level	Concentration (ppm)	DEW line cleanup protocol
CEPA	>50	Shipment to Southern licensed facility
DCC Tier II	5–50	Isolate from the Arctic ecosystem (Northern disposal facility or ship south)
DCC Tier I	1–5	Burial in nonhazardous landfill

A mobile laboratory was set up on site to conduct PCB analysis (Rutter et al., 2003). During excavation, the analysis for PCBs in soil was performed using two shaker methods. The first, longer shaker method was replaced by a modified shaker method in 2004, which was developed to improve turnaround time. In both methods, soils were analysed by accurately weighing 10 g (dry weight equivalent), spiking with an internal standard solution (decachlorobiphenyl). The original shaker method differed in extraction solvent and number of extractions — 50 mL dichloromethane was used and the sample was extracted 3 times for 20 min. The decanted fluid from each extraction was poured through a sodium sulphate filter into a round bottom flask. The extract was then concentrated by rotoevaporation to approximately 1 mL, and a solvent exchange to hexanes was performed. The extract was flushed through a florisil cleanup column and made up to 10 mL. The modified shaker method was performed by extraction with 50 mL of a 1:1 mixture of hexane and acetone for 20 min on a platform shaker. All extracts were analysed by gas chromatography with electron capture detection (GC/ECD). None of the analytical blanks contained any PCBs at concentrations above 1.0 μg/g and all control samples were between 30% of the expected value. Relative standard deviations between the samples and their analytical duplicate were below 30% for all results. Surrogate recovery was within 20%.

2.3. *Soil excavation and remediation*

Excavation followed the grid system wherever possible. Clean roads were constructed to allow access to contaminated soil locations. To build clean roads, contaminated areas were excavated and clean fill added. Where this was not possible or efficient, clean roads were created by placing clean fill on top of Tier II soil without excavation. In this case the clean road and underlying Tier II soil was excavated once the area was completed. These details were mapped daily to keep track of the PCB contaminated soil — any buried Tier II soils were removed during subsequent excavations. Contaminated soil was removed using heavy equipment by initially excavating the first 0–30 cm layer of soil. A composite sample of the excavated area was then obtained and analysed. Excavation continued by removing 30 cm layers until the remaining soil had a PCB concentration below criterion or bedrock was reached. When laboratory analysis confirmed grid squares had been remediated to the appropriate criteria, they were signed off by the scientific officer, site engineer and site superintendent. In most cases, CEPA soil was removed from all grid squares followed by Tier II and then Tier I. The Qikiqtaaluk Corporation, Iqaluit under contract to DIAND (Department of Indian and Northern Development, subsequently INAC, Indian and Northern Affairs Canada), conducted the remediation work.

Three technologies were initially examined for possible use at Resolution Island: incineration, thermal desorption and solvent extraction. The use of all these technologies on site was eventually eliminated after review by the Nunavut Impact Review Board (NIRB), largely due to concerns regarding transport and maintenance of equipment in a harsh environment and the associated environmental and financial risks (Poland et al., 2001). The NIRB is an environmental impact assessment bureau established under Article 12 of the Nunavut Land Claims Agreement (INAC, 1993). Proposals are submitted to the NIRB for projects within the Nunavut Settlement Area. These proposals are initially screened and recommendations are made to the NIRB, which in turn submits its decision to the Minister of Indian and Northern Affairs. The NIRB bases its decision in writing on the four options in accordance with Section 12.4.4 of Article 12 of the Nunavut Land Claims Agreement (INAC, 1993). Excavation of soils and incineration at a southern disposal facility was chosen as the remediation technology for destruction of CEPA soils from BAF-5 (Poland et al., 2001). Remediation protocols modified for Tier I and Tier II soils are described below.

2.4. *Remediation of CEPA soils*

All contaminated areas that were in violation of the CEPA regulations were excavated with diligence to ensure that all soils contaminated at CEPA levels were removed. The geology of the site is fractured gneiss and therefore excavation to bedrock, using only heavy equipment, left significant amounts of soil on the ground. If the remaining soils were contaminated with PCBs at the CEPA level, residual soils were then completely removed using manual labour and a vacuum truck. No visible soil remained on the bedrock in these areas. The topography of the site in the main area of PCB contamination is illustrated in Fig. 3. The volume of excavated CEPA soils was approximately 2500 m^3 in the S1/S4 valley, and 2000 m^3 at the S1/S4 beach area. Remediation at the S1/S4 beach was particularly challenging due to the steep cliff in its upper zone. At the beach location, some CEPA soil was left behind as heavy equipment could not access the entire area due to the steep grade.

All excavated CEPA material was passed through a screener, allowing particles with diameters less than 5 cm to fall through. CEPA materials were sieved to reduce the overall volume of soil that had to be treated. This reduced costs for both shipment south and destruction of the contaminated material. The sieved material was containerised and shipped south for destruction by incineration. The reject material was classified as Tier II material. Approximately 5000 m^3 of CEPA soil was excavated in total from the site, including the valley, beach and other on site contaminated areas. Initially, excavated soil was stored in a lined warehouse facility after screening. Over a period of three years, this stockpiled soil was ultimately containerised into 3.1 m^3 steel containers, loaded by barge onto a ship and incinerated at a disposal facility in southern Canada. Upon the removal of these soils, 96% of all PCBs by mass had been accounted for. The remaining 4% of PCBs was distributed in approximately 15,000 m^3 of Tier I and Tier II soils.

2.5. *Remediation of Tier I and Tier II soils*

Excavation of Tier I and Tier II soils commenced after the CEPA soils were removed. Once excavated, the soils were not screened as cost savings were not significant. Soils were not containerised but placed directly in a Tier II landfill on site as described below. Soils remaining after excavation to bedrock by heavy equipment were not vacuumed. Tier II soil was removed prior to excavation of Tier I soils. In areas with difficult access, Tier I and Tier II soils were removed together.

Excavation of Tier I soils proceeded similarly to that of Tier II soils. In some areas the Tier I soils were excavated to bedrock rather than by 30 cm stages, to facilitate excavation. Two other options were included in the protocol for Tier I soils; disposal in an on site nonhazardous landfill or covered in place with clean fill. At the site, the majority of the Tier I soil was used in the Tier II landfill as intermediate fill and as the initial layer of fill capping this landfill.

An engineered, lined landfill was chosen as the most viable disposal technology for the Tier II contaminated soil on BAF-5.

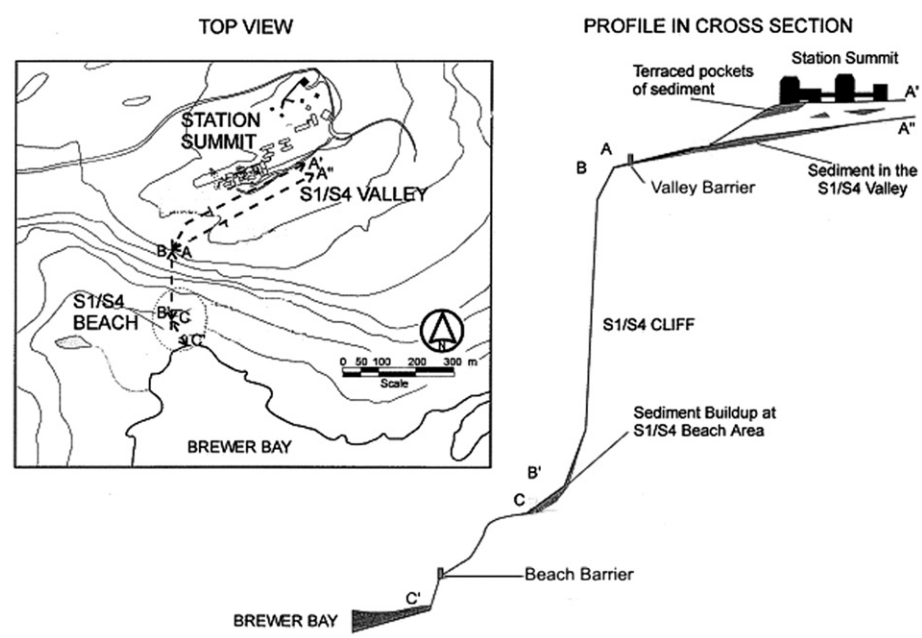

Fig. 3 – Profile of S1/S4 Valley and Beach area.

The use of this option would result in the immobilization of the contaminated soil, effectively removing the contaminants from the Arctic ecosystem. The landfill was lined and designed to contain the contaminated soil in permafrost (Corrigan et al., 2005). Various challenges faced the design and construction of the landfill, such as: selecting a suitable landfill location at this mountainous and widely contaminated site, and the construction of a lined landfill under harsh weather conditions. In total, over 10,000 m^3 of Tier I/Tier II material was excavated and landfilled at the site.

There is essentially no groundwater due to the shallow depth of the permafrost, therefore subsurface remediation was not necessary. However, contamination remains on the island in soils containing approximately 240 kg PCBs after excavation. Some of the soil is trapped in the fractured bedrock and some soil cannot be accessed because it is on very steep terrain that cannot be accessed for logistical and safety reasons.

2.6. *Surface water barrier design and construction*

In 2003, a trial surface water barrier system was installed in the S1/S4 valley to minimize the migration of PCB contaminated particulates and any dissolved or suspended PCB oils transported by surface water. It incorporated gabions and geosynthetic liners, which formed the funnel, and a 0.82 m wide stainless steel gate (Fig. 4). The design concept was based on previously reported funnel-and-gate barrier systems (Starr and Cherry, 1994), but altered for surface water remediation. The wide funnel mouth was designed to enable better entrapment of the contaminated runoff, and would help to slow down flow and deposit contaminated soils. Ideally, the first portion of the gate would filter out contaminated fines and the latter portion of the gate would treat PCB contaminated water through a combination of geotextiles and geosynthetic filter materials, listed in Table 2. The gate consisted of a stainless steel box into which up to four filter cassettes could be placed (Fig. 5a–d). A clean cell was installed directly behind the barrier to help monitor barrier efficiency.

The location of the barrier in the S1/S4 valley was chosen early in the field season when water was still running in the valley. The valley has two separate drainage pathways which merge at the barrier site and then again form two separate pathways once they pass through this narrow point of the valley. The site was also selected because the gradient was sufficient to allow a pool to be formed upstream of the gate once the funnel was built.

2.7. *Construction of trial surface water barrier*

The initial task in the installation was to establish the base plate on which the gate would sit. Once the area was excavated, 1.3 cm steel reinforcing-bar rods were bolted to the bedrock and then a concrete foundation was poured. A stainless steel base plate (0.9 m × 1.5 m) could then be bolted to the steel rods protruding through the concrete base.

Fig. 4 shows the funnel and gate design concept that was used for the barrier construction on site in 2003. Contaminated drainage water would first flow through gabions and over a mat in order to trap particulate matter. Water and entrained particulate matter would then be contained by the "funnel" and forced to pass through the filter box or "gate". The box consists of four pairs of slots into which filters or cassettes containing absorbing material can be placed. The steel boxes

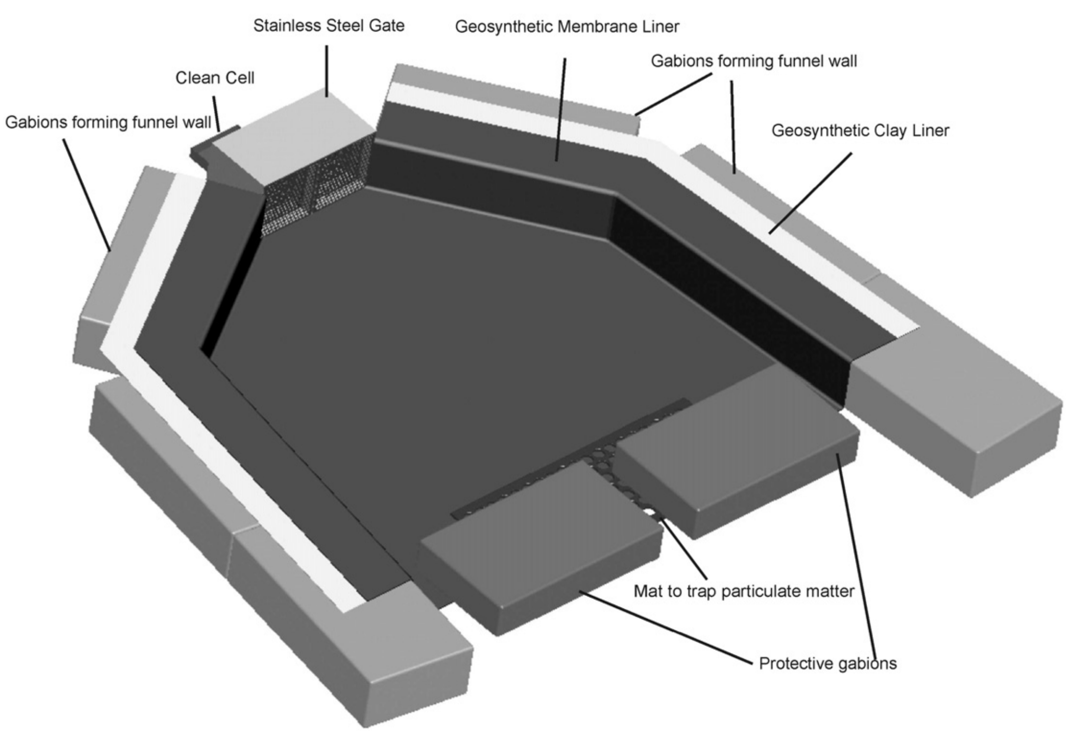

Fig. 4 – Prototype barrier design 2003.

Table 2 – Filter materials examined (k = hydraulic conductivity, EOS = equivalent opening size, μ = mass per unit area, t_{GT} = thickness of geotextile from Terrafix) Kalinovich et al. (2008)

Filter	Type	Relevant properties
W1	Polypropylene slit-film woven geotextile	EOS = 0.6 mm $k = 3.3 \times 10^{-4}$ m/s $\mu = 82$ g/m^2 $t_{GT} = 0.61$ mm
W2	Polypropylene slit-film woven geotextile	EOS = 0.6 mm $k = 1.0 \times 10^{-4}$ m/s $\mu = 210$ g/m^2 $t_{GT} = 0.67$ mm
NW1	Nonwoven, polypropylene needle-punched geotextile	EOS = 50–150 μm $k = 1.5 \times 10^{-3}$ m/s $\mu = 730$ g/m^2 $t_{GT} = 4.65$ mm
NW2	Nonwoven, polypropylene needle-punched geotextile	EOS = 50–150 μm $k = 1.9 \times 10^{-3}$ m/s $\mu = 690$ g/m^2 $t_{GT} = 4.24$ mm
Hydrophilic geosorbent	Booms, 7.6 cm diameter, polypropylene	–
Hydrophobic geosorbent	2.54 cm shredded bluepolypropylene	–
GAC1	Granulated activated carbon	2–3.35 mm particle size
GAC2	Granulated activated carbon	2 mm particle size
Gravel	Granular	2–8 mm particle sizes 6.4–12.7 mm particle sizes.

were built using 1.6 mm stainless steel panels. All sections of the stainless steel boxes were bolted together so that the units could easily be modified at a later date. The lids of the boxes were painted black to increase the temperature within the barrier through sunlight exposure, so that any frozen material would melt more quickly than in the surrounding area thereby encouraging flow through the gate.

Seven materials were chosen and placed in the various filter slots in each barrier. The first filter was a woven geotextile, with an equivalent opening size of 0.6 mm. The second filter was a needle-punched nonwoven geotextile, with an equivalent opening size of 50–150 μm. The two filter boxes (shown in Fig. 5) contained different materials in the third filter slot. The third filter contained either granulated active carbon (GAC) or a shredded, hydrophobic geosorbent as an adsorption agent in a 2.5 cm thick cassette constructed of polypropylene. The final filter contained four hydrophilic absorbent booms (1 m long with a diameter of 12 cm) in a 7.6 cm thick cassette; two of these cassettes were used and placed in each side of the gate. All filters and their properties are outlined in Table 2 and are described in detail in Kalinovich et al. (2008).

Prior to barrier construction, the area that would form the funnel was tested for PCBs and found to be Tier II in some locations. This soil was excavated and the funnel area filled with clean fill. The funnel walls were formed using 3 gabions (2 m × 1 m × 0.5 m) on each side. These gabions were bolted to the bedrock prior to being filled with rocks. Once filled, the gabions were joined and sealed with wire lacing. Once the frame of the funnel was complete, the liners were positioned. The base was formed by two layers of geosynthetic clay liner (GCL) containing bentonite clay. The GCL used in this design comprised of a thin layer of bentonite between two nonwoven needle-punched geotextiles.

The GCL was laid on the reservoir floor and up the sides of the gabions to ensure that water was directed to the gate. The GCL layers were then saturated with water to create a watertight seal for the funnel. A flexible liner (laminated polyurethane, nylon and polypropylene) was placed on top of the GCLs and sandbags were placed on top of the gabions to hold down the liners on top and as they were toed in behind the gabions. The liners were toed into the ground at the front of the funnel and a rigid silt trap mesh overlaid this area. Smaller gabions (2 m × 1 m × 0.3 m) were then installed over the end of the liners at the entrance to the funnel to prevent rocks and debris from clogging the barrier. These gabions further secured the liners to the ground. The silt trap mesh was secured by the gabions and extends into the funnel area to trap soil that passes through the gabions.

After the liners were in place, the two metal boxes, which formed the gate, were bolted to the stainless steel plate. The liners were secured to the boxes by folding them under a polyethylene strip, which was bolted onto the boxes. At this point the filters were installed. A clean cell was constructed directly behind the gate. It consisted of an area bounded by a wooden frame and filled with sandy soil which contained no PCBs. Any PCBs passing through the system (either as adsorbed onto soil particles or in water) would contaminate this clean soil. The soil in this clean cell could be analysed and results used to gauge the performance of the funnel and gate system.

2.8. *Surface water barrier modifications*

In 2004 it was realized that increased sediment removal was required. The high sediment loadings were causing clogging and reducing both filtration and sorption efficiencies. The design scheme was altered (Fig. 6a and b) to improve its performance. The design was modified to increase the capacity for soil retention within the funnel prior to reaching the gate. The first design amendment consisted of increasing the area within the funnel.

This was achieved by lengthening the funnel sides to create a second pond. By increasing the ponding area, it became possible to trap contaminated soils further upstream, prior to reaching the gate. Flow impediments in the form of chevrons were constructed upstream from the funnel area. These chevrons were designed to help channel the water towards the barrier system, trap contaminated sediment and reduce flow velocity. The design of the chevrons made it possible to retain and stabilize soil particles as well as promote vegetation growth. Geosynthetics offer immediate soil protection and once installed provide a framework that can be integrated with established vegetation for a longer-term erosion control solution (Theisen, 1992).

Coarse aggregate was spread in front of the barrier system to help widen the flow path, and to even out and reduce

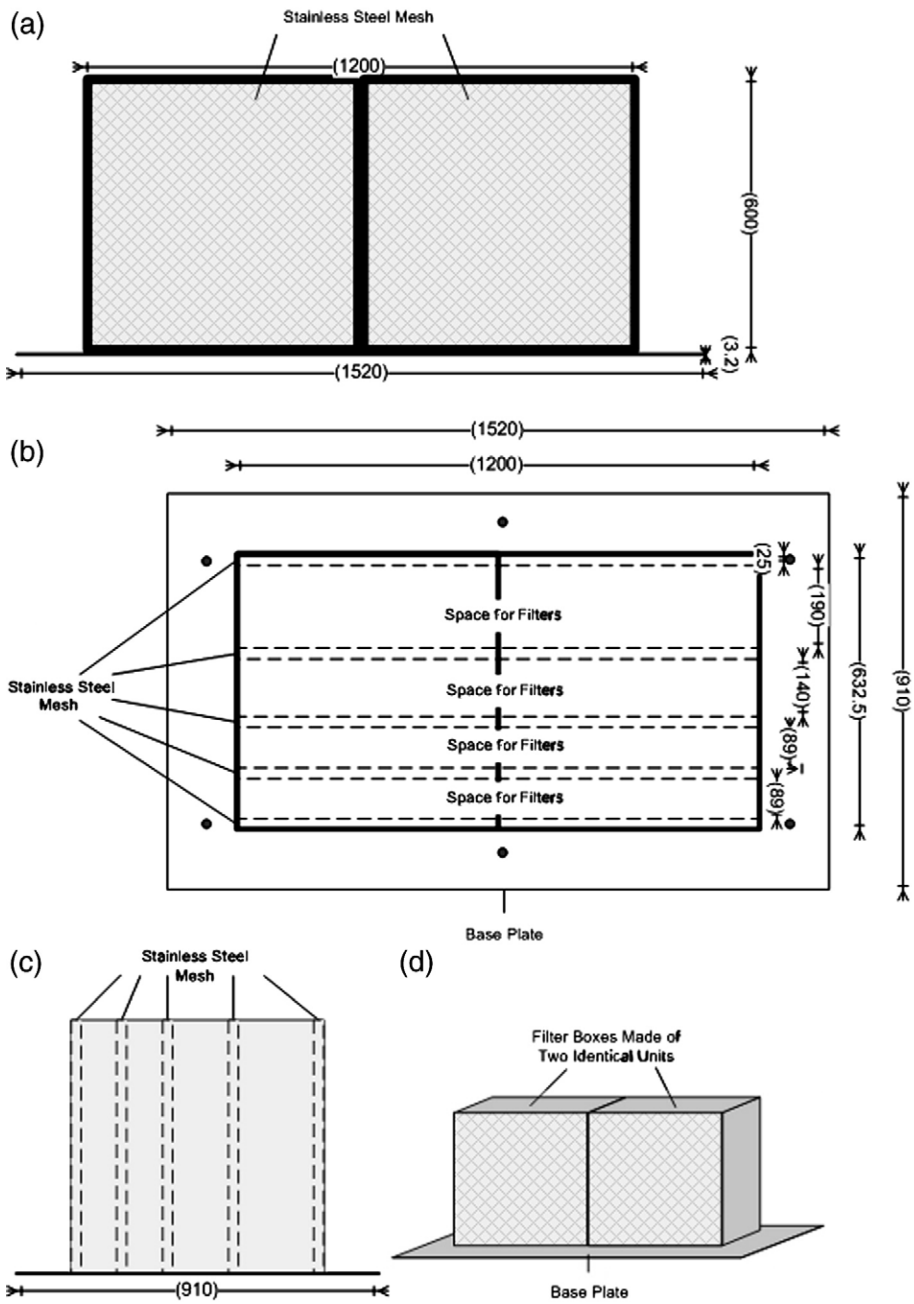

Fig. 5 – a–d. Prototype barrier gate design 2003 a) front view b) top view c) side view d) full unit. Dimensions given in mm.

overall flow velocity (Woinarski et al., 2003). A gabion lined with a slit-film woven polypropylene geotextile (W2 shown in Table 2) was placed 5 m upstream from the chevrons to trap soil.

Sections of hard, black 60 mil HDPE liner were cut out to fit the inside of both ponding areas. These were set in place to help protect the underlying liner from rock fall and as well from rips and tears that may occur during sediment removal.

The bedrock topography of the northern barrier wall has a much steeper slope that is approximately a 0.5 m drop at the mouth of the funnel. The majority of the water came directly through the channel in which the barrier was constructed. A directional flow aid was required to ensure that water on this higher section of the valley is directed to flow towards the barrier (Fig. 6a and b). This came in the form of a berm and a constructed flow impediment. The berm (1 m×3 m×0.5 m) was constructed utilizing the Tier I level debris rock (particle size radius >20 cm) and clean fill from the area (Fig. 6a and b). In front of this berm another flow impediment, sediment trap structure was placed. This structure was 3 m in length and wrapped in a slit-film woven polypropylene geotextile (W2 shown in Table 2). The ground naturally sloped towards the barrier funnel with a 1 m drop in elevation to the first ponding area. The construction of the flow impediments made certain that in times of excess flow, the preferential flow path remained channelled towards the funnel of the barrier.

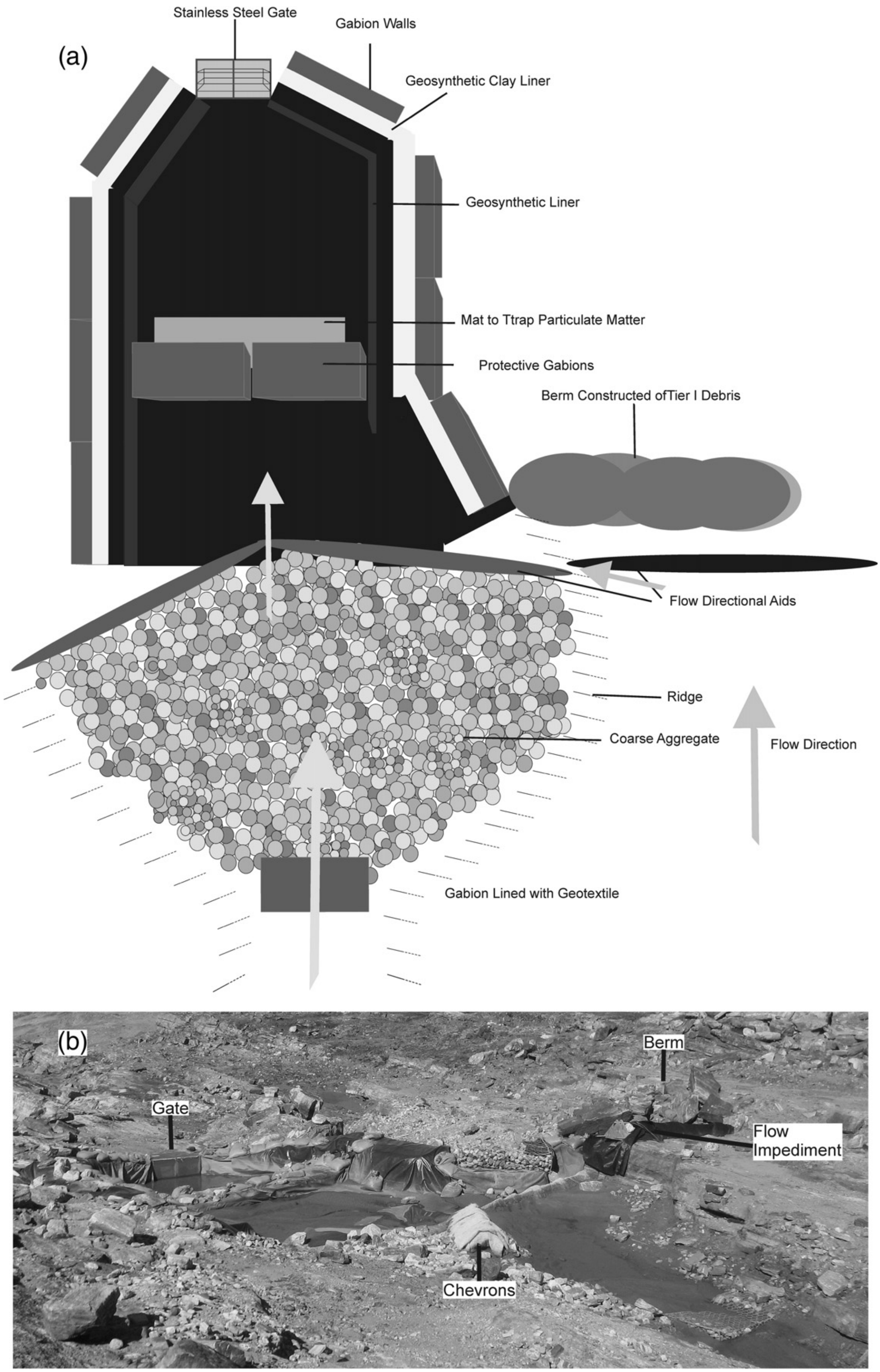

Fig. 6 – a and b. Modified barrier design 2004.

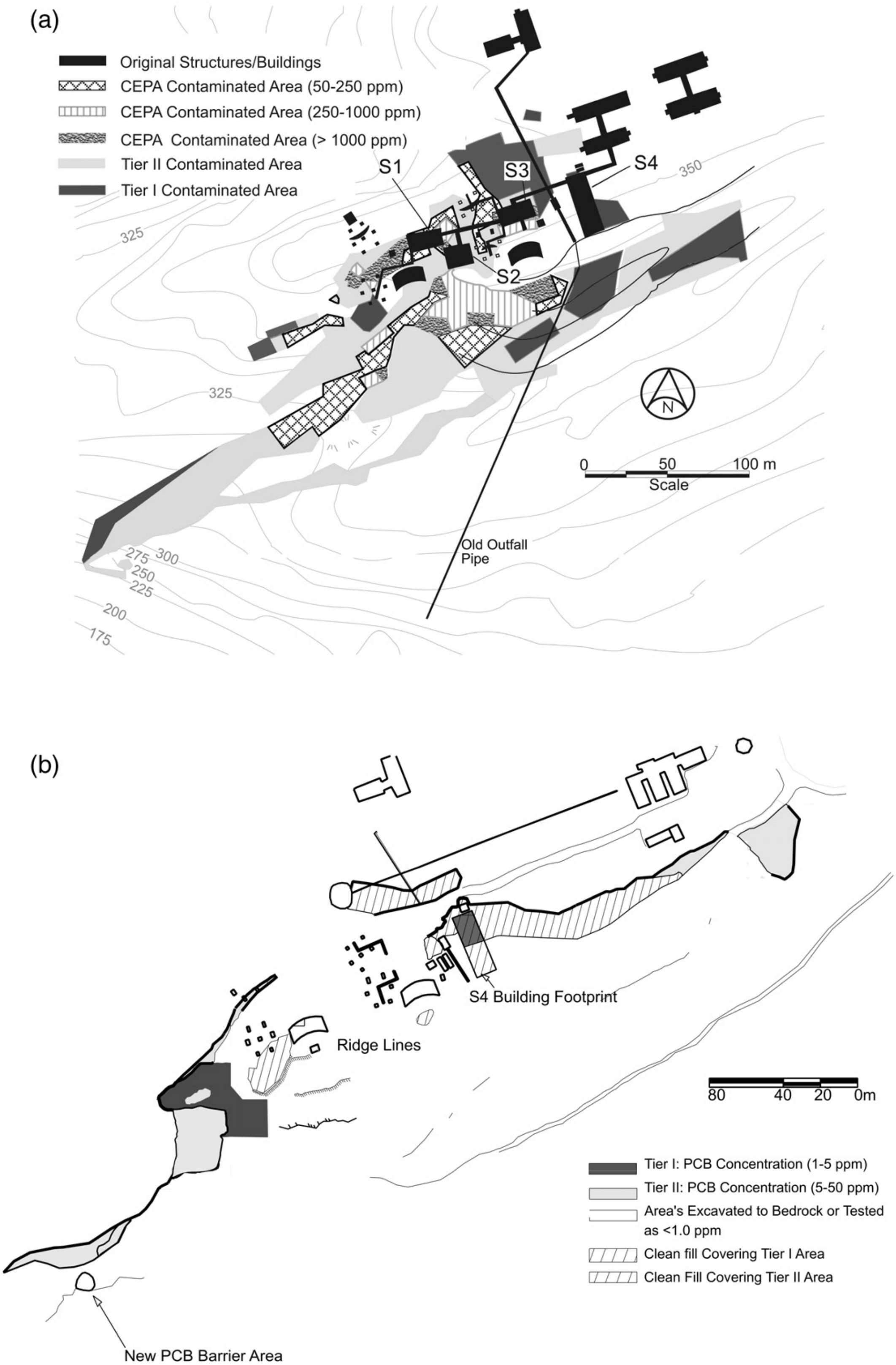

Fig. 7 – a and b. GPS maps showing before (1996, 7a) and after (2005, 7b) excavation. S1/S4 refer to buildings. Buildings were present in 1996 and removed by 2005.

3. Results and discussion

3.1. Excavation and remediation

Fig. 7a and b shows the beginning and ending of excavation efforts over the period of 1996–2005 at BAF-5 for the S1/S4 Valley.

By the end of the 2005 field season, all soils contaminated with PCBs at concentrations greater than 1 ppm which could be excavated by heavy equipment had been removed. In areas where excavation was not possible, Tier I (1–5 ppm) soils were covered with clean fill. PCB contamination was not present at depths below 1 m and generally there was little surface soil above bedrock.

3.2. Sediment collection in PRB funnel

In June 2004 the first observations of how the barrier would perform under spring melt runoff conditions were obtained. It was observed that the amount of mobile contaminated soils greatly exceeded expectations and that the gate became clogged with PCB contaminated silt. The first pond had a capacity to trap 7 m^3 of material (including both soil and water). The funnel area was increased in order to facilitate sedimentation processes upstream from the permeable gate designed using Stokes' Law, viz:

$$\upsilon_t = \frac{gd^2\left(\rho_p - \rho_w\right)}{18\mu} \quad (1)$$

where υ_t is the terminal settling velocity (m/s), g is acceleration of gravity (m/s^2), ρ_p is the density of the particle (g/m^3), ρ_w is the fluid density (at 5 °C) (g/m^3), d is the diameter of the particle (m) and μ is the medium viscosity (kg/ms). The value of υ_t can be used in the following equation to solve for the Reynolds number:

$$N_R = \phi\upsilon_t d/\mu \quad (2)$$

where N_R is the Reynolds number and ø is the shape factor (equal to 2 for a sand) (Gregory et al., 1999) and other terms are as defined previously.

The use of Stokes' law is not appropriate for Reynolds numbers that are greater than 1.0. Under these conditions, the Reynolds number falls into the transitional region (N_R=1 to 2000) (Metcalf and Eddy, Inc., 2003). Therefore, the following equation was used to calculate the drag coefficient, C_d:

$$C_d = \frac{24}{N_R} + \frac{3}{\sqrt{N_R}} + 0.34. \quad (3)$$

The drag coefficient can be used in the modified Newton Equation

$$\upsilon_t = \sqrt{\frac{4g}{3C_d\phi}\left(\frac{\rho_p - \rho_w}{\rho_w}\right)d} \quad (4)$$

to calculate the settling velocity.

Iterative calculations were conducted until the particle settling velocity calculated from the drag coefficient Eq. (3) was equal to an assumed particle settling velocity. When the settling velocity used to compute the Reynolds number agreed with the settling velocity value from the modified Newton's Eq. (4), the solution value was confirmed.

The area of the funnels was maximized as much as topography would allow. Given that the cumulative area (*A*) of the funnel of the valley barrier was 14 m^2 with an average flow rate (Q) of 1 L s^{-1} through the area it was possible to calculate a particle settling velocity specific to that system where υ_c is the overflow rate (m^3/m^2d). The parameter υ_c is difficult to measure at BAF-5 as it is a phenomenon that occurs when no personnel is on site and therefore must be theoretically calculated.

$$\upsilon_c = \frac{Q}{A}. \quad (5)$$

The fraction of particles with the settling velocity that are removed (X_r) can be calculated via:

$$X_r = \frac{\upsilon_t}{\upsilon_c}. \quad (6)$$

By calculating the settling velocities of particles of varying sizes it was possible to design the first pond such that particles with a grain size greater than 0.4 mm would settle out, thus allowing clean water to overflow the system. This corresponds to trapping 57% of the suspended particles in surface runoff through the process of sedimentation (Fig. 8).

The soil loading that was trapped in the funnel system in 2004 was estimated to be 2.5 m^3. Using an approximate soil density of 1.8 g/cm^3 and an average soil concentration of 18 μg/g (1260 Aroclor), the mass of PCB trapped by the funnel was 81 g. It was found that this amount of sediment loading on the system severely hindered the performance of the more permeable gate. The flow rate through the clean (no sediment present) barrier averaged 0.0015 m^3 s^{-1}. As the barrier gate filled up with contaminated particulate, this flow rate through the gate decreased. As a result, sediment accumulated and was deposited at the gate, thereby severely reducing the hydraulic capacity of the gate.

Modifications to increase the funnel as described in the methods section of this paper were conducted in August of 2004. Modifications were limited by topography and therefore were able to only double the capacity of the barrier funnel. With the addition of the second pond, it became possible to capture particles greater than 0.2 mm diameter — now 70% of the soil fraction could be trapped through the process of sedimentation. By further reducing the amount of material that had to be dealt with in the gate, the hydraulic performance of the gate was increased and therefore the overall performance of the barrier system was improved. After calculating the percentage of soil fraction trapped via sedimentation, it was determined that further modifications to enhance overall sedimentation prior to the funnel were required in efforts to prevent clogging of the system.

Both the coarse aggregate and chevron-shaped sediment traps constructed of geosynthetics placed upstream from the second funnel helped to reduce the flow velocity and increase trapping of contaminated soils. A moss, *Distichum capillaceum*, has started to grow on the southern face of the chevron flow impediments. It has been shown that mosses have the capacity to uptake PCBs from both atmospheric deposition as well from the soil (Lim et al., 2006; Borghini et al., 2005; Blais

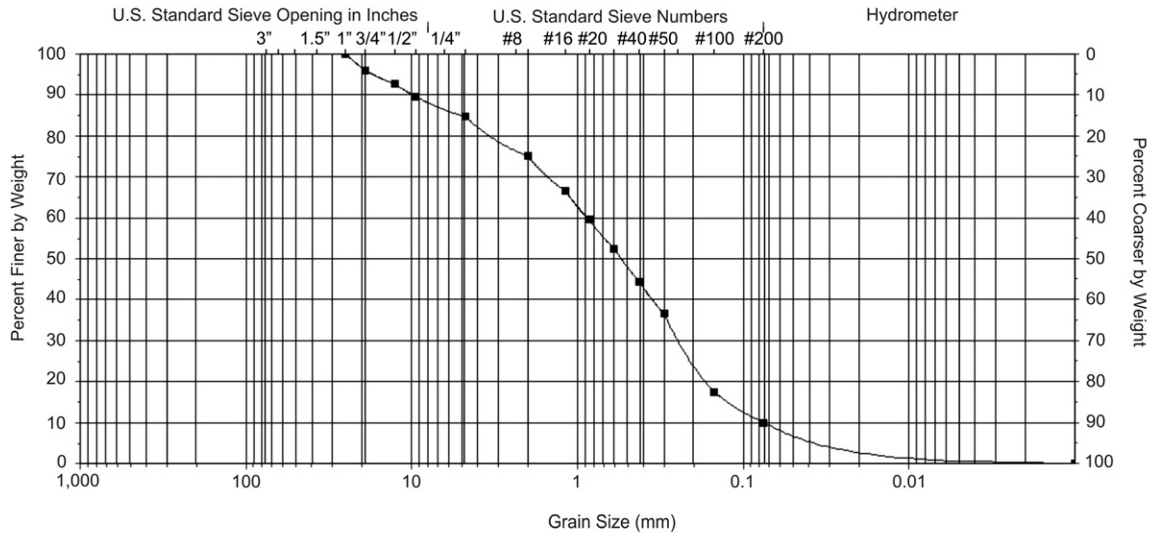

Fig. 8 – Soil grain size distribution graph, S1/S4 valley.

et al., 2003). Regardless of the PCB uptake from the soil, plant matter helps to stabilize the soil upstream from the barrier and increases sedimentation processes by reducing re-suspension of sediments (Rickson, 2006). It should however, be stressed that other factors, such as sediment and hydraulic load have a greater influence on the retention performance than vegetation (Braskerud, 2001).

In June of 2005, it was observed that the modifications to the barrier system were successful in retaining contaminated soils without hindering hydraulic flow through the permeable reactive gate. In total, 7 m^3 of Tier II material was collected in the barrier system during the period September 2004 to June 2005. A calculated amount of 60 g of pure PCB was retained by the funnel when using an average soil concentration of 4.8 μg/g (1260 Aroclor).

The highest amounts of soil erosion were expected during the spring runoff in 2005, as loose uncompacted soils had resulted from the excavations occurring throughout the valley. The amount of sediment will be reduced significantly over the next few years, as natural processes such as plant growth and compression by snow pack, compact and stabilize soil pockets. This will enable additional geosynthetic sorbent and geotextile filters to be re-introduced into the gate.

Data collected in 2004–2007 for sediment trapped in the funnel, average PCB concentration and the total mass of PCBs are shown in Table 3. The reduction of both volume of soil and mass of PCBs indicates the barrier is working well.

Table 3 – Sediment trapped in S1/S4 valley barrier, average PCB concentration and total mass of PCBs

Year	Volume of sediment (m^3)	Average PCB concentration in sediment (μg/g)	Mass of PCBs in sediment (g)
2004	2.5	18 ± 12	81 ± 54
2005	7.0	4.8 ± 2.3	60 ± 29
2006	2.2	5.9 ± 4.0	23 ± 16
2007	1.0	5.1 ± 1.3	9.3 ± 2.4

3.3. PCBs trapped in gate

The amount of PCB captured year to year in the gate varied depending on activity occurring in the field as well as filter materials present in the box. For 2003, filters were installed in July of 2003 and were removed and analysed in September of 2003 — these filters did not experience spring melt, only summer storm events. The filters retained 379 mg of PCB (shown in Table 4). In 2004, both Tier II as well as CEPA soils remained in the valley, accounting for a high presence of PCB in the barrier funnel system. From Table 3, it was seen that 81 g of PCB was removed from only 2.5 m^3 of soil from the funnel. Much of the CEPA soils had recently been excavated and since the areas were vacuumed, the migration of highly contaminated PCB fines had been greatly reduced. In June of 2004, the high sediment loading and the presence of a 0.6 mm EOS nonwoven polypropylene geotextile at the very front of the gate hindered barrier performance to the extent that water and contaminated soil barely moved through the filter system. In this year, only 35.9 mg of PCB was retained by the filter system. It was realized at this point modifications to both filter materials as well as the filter funnel would be required. Filter materials were overhauled in 2004 with a shift to a more permeable, granular system. In 2005, it was seen that the granular system worked well with the increased sediment loading from excavating and stockpiling of Tier II contaminated soils near the barrier. In 2005, even though 7 m^3 of Tier II contaminated soils were removed from the funnel, the gate

Table 4 – Total mass of PCBs in S1/S4 valley barrier gate (values within 30% limits)

Year	Mass of PCBs in gate (mg)
2003	379
2004	35.9
2005	313
2006	128
2007	289

managed to perform well enough to capture 313 mg of PCB without clogging. Excavation activities ended in 2005 and therefore both soil loading in terms of volume and mass of PCB were greatly reduced for 2006. In 2006, the filter system retained 128 mg of PCB. In order to accommodate the volume of soil loading while maintaining hydraulic flow, larger particle size (6.4 to 12.7) gravel filters were favoured over smaller particle sized granulated activated charcoal (GAC) filters (2 to 3.35 mm). After 2006 the reduction of sediment loading allowed for an emphasis on trapping contaminated fines by using the finer particle sized GAC filters. The filter system in 2007 was found to trap 289 mg of PCB. Fig. 9 shows the total volumes of soil and mass of PCBs collected from 2005–2007 from both the funnel and filters.

The reductions in volume of sediment and mass of PCB are to be expected with the completion of the site remediation and the concurrent soil stabilization. Since sediment loading has lessened, optimized trapping of fines can be the focus of future improvements. At the end of the 2007 field season, nonwoven geotextiles were re-introduced back into the gate as the most downstream filter to trap fines in combination with GAC filters. Their performance will be evaluated in 2008.

3.4. *Monitoring plan*

A monitoring plan was instigated along the drainage pathway both upstream and downstream from the barrier system to monitor changes in soil concentration of PCBs. Results presented in Table 5 show that as expected, small amounts of soil downstream remain at Tier II concentrations. In terms of groundwater permeable reactive barriers, contamination present downstream of the barrier would imply an improper location of the barrier that did not successfully encompass the area of contamination (Blowes et al., 2000). However, in terms of surface remediation where topography and safety become a factor in the emplacement of such a system, trade-offs between worker health and safety and environmental remediation must be made (Ashford, 1998). Areas of Tier II concentration that were excavated downstream of the barrier were not remediated to clean bedrock — therefore pockets of mobile Tier II soil remained. These pockets of contaminated material re-distribute themselves seasonally with both spring runoff and summer rain events.

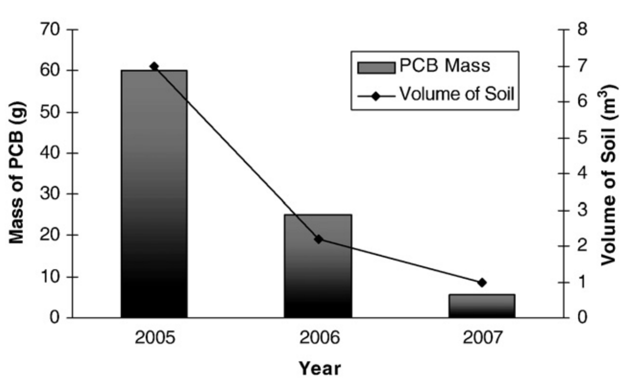

Fig. 9 – Mass of PCB and volume of soil removed during the period 2005–2007.

Table 5 – Monitoring soil points in S1/S4 valley barrier

	PCB Concentration (μg/g)			
	2004	2005	2006	2007
Upstream of chevrons	12	7.4	1.3	4.5
Between chevrons and Gabion Fence	–	3.3	8.7	3.7
Upstream of gate	11, 13, 37	3.7	7.6	5.3, 6.7
Within gate between first two filters	–	37	5.0	–
Clean cell	3.9	2.6	–	–
Second clean cell (30 m downstream of barrier)	–	–	–	3.8

Clean cells were installed directly behind the barrier and further downstream to help better monitor barrier efficacy. Due to the large volume of water that travels through these areas during spring runoff, soil is not always present in these clean cells for sampling and analysis. In the case of the cell downstream, it is not certain how much of the Tier I material found in the cell is from the barrier or from re-deposited soils from the Tier I/Tier II soils adjacent.

From the monitoring results, it was seen that the barrier system since the 2004 modifications has not contributed to an increased PCB concentration downstream from the barrier, indicating that the barrier is itself not becoming a source of contamination. This modified system has proven to be successful in trapping by sedimentation processes alone, over 790 g of pure PCB in 12.7 m^3 of contaminated soil during the period 2003–2007. Based on the success of the 2004 barrier design, further permanent barrier systems were installed in two other locations on site: one further downstream from the valley barrier, at the base of a 350 m cliff, to trap contaminated sediment prior to entering the Arctic ocean and one in an area that was highly contaminated with PCB, with little sediment deposits left.

3.5. *Economics*

Costs are estimated for the entire project — including areas other than the S1/S4 valley. However, the bulk of the cleanup at this site had to do with remediation of PCBs and the excavation and disposal of the soils from the S1/S4 Valley drainage area so the values given are excellent indicators of the remediation described in this paper. The total cost for the project (1997–2007) was $64.75 million with 595 persons employed. BAF-5 is a highly remote site, as indicated by the costs for construction/support and transportation which account for 60% of the total costs. As of 1997, the project experienced Inuit employment levels above 85%. Costs associated by PCB contaminated levels are as follows: an estimated $12 million to deal with CEPA level of contaminated materials, $6 million to deal with Tier II materials and $2 million to deal with Tier I materials.

4. Conclusion

The remediation of PCB contaminated soils at a remote site with an extreme climate such as BAF-5 has been successful. In total, 5000 m^3 of CEPA contaminated soil was excavated and shipped off site for destruction by incineration, and 15,000 m^3 of Tier I/Tier II materials have been excavated and removed from the Arctic ecosystem by placement in an on-site lined landfill. A long-term remediation and monitoring plan has been set up on site, which included the construction of surface funnel-and-gate permeable reactive barriers. Modifications to barrier design to improve capacity for soil loading were required in 2004. These modifications proved highly successful in trapping and retaining PCB contaminated soil. Monitoring results demonstrate that the barrier itself is not a source of contamination and appears to be retaining the contaminated soil effectively.

These results indicate that this type of barrier system works well in conjunction with excavation to trap destabilized, mobile contaminated soils. The barrier design is adaptive and can be modified to coincide with changes in field conditions to enable optimal barrier performance. The barrier system described in this paper is an adaptation of the funnel-and-gate permeable reactive barrier remediation technology more commonly used to treat groundwater and is the first system of its kind to be used in cold regions. Results and lessons learned from this paper can be used to optimize further surface barrier systems.

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