

Maria E. Granberg, Amalie Ask and Geir W. Gabrielsen

Local contamination in Svalbard

Overview and suggestions for remediation actions





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The Norwegian Polar Institute is Norway's central governmental institution for management-related research, mapping and environmental monitoring in the Arctic and the Antarctic. The Institute advises Norwegian authorities on matters concerning polar environmental management and is the official environmental management body for Norway's Antarctic territorial claims. The Institute is a Directorate within the Ministry of Climate and Environment.

Norsk Polarinstitutt er Norges hovedinstitusjon for kartlegging, miljøovervåking og forvaltningsrettet forskning i Arktis og Antarktis. Instituttet er faglig og strategisk rådgiver i miljøvernaker i disse områdene og har forvaltningsmyndighet i norsk del av Antarktis. Instituttet er et direktorat under Klima- og miljødepartementet.

Maria Granberg
Present address:
maria.granberg@ivl.se
Natural Resources & Environmental Effects
IVL Swedish Environmental Research Institute
Sven Lovén Centre for Marine Infrastructure
Kristineberg 566
451 78 Fiskebäckskil
SWEDEN

Amalie Ask
Present address:
amalieask@gmail.com

Geir W. Gabrielsen
geir.wing.gabrielsen@npolar.no
Norwegian Polar Institute
Fram Centre
Postbox 6606, Langnes
9296 Tromsø

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Framsenteret, NO-9296 Tromsø, Fram Centre, NO-9296 Tromsø
www.npolar.no, post@npolar.no

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BACKGROUND

As part of the tasks for the Polar Regions stated in the 2016 award letter from the Ministry of Climate and Environment the Norwegian Polar Institute (NPI) was assigned to:

“Compile experiences from already performed remediation actions of contaminated localities in Svalbard and evaluate current remediation methods based on experience and literature from areas with an Arctic climate and limited possibilities for deposition of contaminated soil”
(Translated from Norwegian).

The task is constrained to cover contaminated soils in Svalbard. Terrestrial systems are, however, intimately connected with watersheds, which drain into coastal marine areas often with marine sediments as main recipients. The interaction between the terrestrial and marine environments is particularly pronounced in the Arctic where human and industrial activities traditionally are situated along the coasts for logistic and habitual reasons. Coastal areas and watersheds are therefore affected by polluted terrestrial systems and will in part be discussed in this report.

This report is based on available reports, published case studies and peer reviewed research articles from Arctic and Antarctic sites. Descriptions of contaminated sites in Svalbard are based on available reports, the Norwegian Environment Agency’s database on contaminated ground sites in Norway, peer reviewed research articles and personal communication with the pollution advisers at the Governor of Svalbard. In several cases full documentation regarding investigations and remediation actions at contaminated sites in Svalbard has not been accessible to the authors and historical data and documentation may yet exist. It is further important to note that the ground pollution database may not provide a complete picture of the contamination situation, since unreported contaminated or remediated sites have not been included and document links may not be complete (Eli Mathisen pers. comm.).

This report should be considered as a starting point for further investigations into local pollution issues in Svalbard. The report also provides initial guidance on how to approach remediation of polluted sites in Svalbard.

ABSTRACT

The Norwegian Polar Institute (NPI) was assigned by the Ministry of Climate and Environment to compile experience from already performed remediation actions of contaminated localities in Svalbard, and evaluate current remediation methods based on experience and literature from areas with an Arctic climate and limited possibilities for deposition of contaminated soil. This report is based on existing reports, published case studies from Arctic and Antarctic Regions, peer reviewed research articles and the Norwegian Environment Agency's database on contaminated ground sites in Norway. The report aims to 1) provide a brief review of polluted sites and their sources in Svalbard, 2) describe current available remediation techniques, and 3) offer brief guidance on future actions regarding polluted sites in Svalbard.

Arctic pollution research and management traditionally focus on the long range transport (LRT) of contaminants from industrialized southern regions to the pristine uninhabited north. Fortunately, environmental concentrations of LRT-related legacy POPs are decreasing in the Arctic following international bans. However, legacy contaminants are being replaced by contaminants of emerging concern (CECs). These CECs are chemicals currently in use and local sources therefore become highly relevant for Arctic pollution. We also observe that unremediated sites harbouring local pollution from historical human activities, such as abandoned settlements, mining areas and military installations may become important contributors to Arctic pollution. These sources have often transgressed from confined contaminated sites to extended diffuse sources, having been allowed to spread over large areas to soil, ground water, watersheds, sediments and biota for decades.

A multitude of investigations have been performed in Svalbard, mapping contamination of traditional contaminants and performing risk assessments showing various degrees of contamination from mining activities (acid and heavy metal drainage), petroleum exploration and fuel storages (petroleum), and garbage dumpsites (PAH, PCB, pesticides, heavy metals etc) at all settlements and also in remote areas. Many sites are multi-polluted and some have already been subject to remediation actions. However, a number of historical industrial sites lack background documentation and proper evaluations of contamination risks are presently challenging to make.

Norway has a well-developed system for classification and risk assessment of contaminated ground sites developed for the temperate mainland. A corresponding system is not fully developed for the Norwegian Arctic. The Arctic presents unique challenges, which make obvious remedial choices difficult or even impossible to implement. There are also knowledge gaps concerning development of Arctic risk assessment models and the information required performing them such as fate and effects of contaminants in Arctic ecosystems and migration rates of contaminants through permafrost. Knowledge is only starting to be gained regarding challenging issues such as landfill construction and bioremediation in cold climates. Based on Arctic and Antarctic bioremediation studies, the most important conclusion here is that remediation solutions are site specific, and that the possible choices for remediation methods primarily rest on the type of contamination present. For highly persistent contaminants such

as PCBs and metals, options are fewer than for contaminants that are actually degradable. *In situ* remediation/ bioremediation options are worth exploring, e.g. in cases of petroleum pollution.

Several successful bioremediation projects have been performed under Arctic and Antarctic low temperature *in situ* conditions, implying both lower costs and efforts but requiring extended time for biological processes to act. Bioremediation is further becoming urgent in the light of climate change. The movement of POPs is slowed down in cold or frozen soil and water. Arctic soils thus sequester contaminants, which are ready to be released and enter food chains as temperatures increase. Arctic dumpsites often rest directly on the ground using the permafrost as a barrier to prevent contaminants from entering the ground and groundwater. With rising temperatures this barrier is broken. In this light it is advisable not to delay impending remediation actions in the Arctic.

Finally, remediation concerns already contaminated environments. We own the opportunity to assess suspected contamination issues of CECs before they become hazards, by exercising the precautionary principle advocated in the Svalbard Environmental Protection Act. Such proactive initiatives require good intentions and active choices regarding, e.g. energy options, sewage treatment and transportation alternatives.

LIST OF ABBREVIATIONS

ADEC	Alaska Department of Environmental Conservation
As	Arsenic
BFR	Brominated Flame Retardants
BTEX	Benzene, Toluene, Ethylbenzene, and Xylenes
Ca	Calcium
CAD	Canadian dollars
Cd	Cadmium
CEC	Contaminants of Emerging Concern
CEPA	Canadian Environmental Protection Agency
Cr	Chromium
Cu	Copper
DDT	Dichloro Diphenyl Trichloroethane (Organochlorine insecticide)
DEW Line	Distant Early Warning system Line
DLCU	DEW Line Clean-Up
DW	Dry Weight
EDTA	Ethylene Diamine Tetraacetic Acid (Chelating agent)
EPA	Environmental Protection Agency (often referring to the United States EPA)
EPA 16PAH	16 PAH compounds from the United States EPA standard list
Fe	Iron
HCH	Hexachloro- CycloHexane (Organochlorine pesticide)
Hg	Mercury
K	Potassium
Mn	Manganese
Na	Sodium
Ni	Nickel
OPFR	Organophosphate Flame Retardants
PAH	Polycyclic Aromatic Hydrocarbons
Pb	Lead
PCB	PolyChlorinated Biphenyls
PCB ₇	Sum of seven standard PCBs
PRB	Permeable Reactive Barrier
PPCP	Pharmaceuticals and Personal Care Products
PFAS	Per- and PolyFluoroAlkyl Substances
PFC	PerFlourinated Chemicals
PFOA	Perfluorooctanoic Acid
pH	<i>Lt: pondus Hydrogenii</i> (a scale for acidity or basicity of an aqueous solution)
POP	Persistent Organic Pollutant
SCCP	Short Chained ChloroParaffins
SVE	Soil Vapour Extraction
SVOC	Semi Volatile Organic Compounds
VOC	Volatile Organic Compounds
Zn	Zink

INTRODUCTION

All human activities leave traces in the environment, and most of our modern civilization activities result in some type of pollution. Pollution research in the Arctic has traditionally focused on the long range transport of pollutants from the industrialized middle regions to the pristine uninhabited north (e.g. MacDonald et al, 2000). This impact has of course been considered unacceptable and unfair since pollution sources were absent in the Arctic. Today we observe that local pollution from historical and present day human activities constitute important pollution sources in the Arctic. Local sources of contamination obviously raise concern at the local level. However, as direct emissions of legacy persistent organic pollutants (POPs) such as PCB, HCH, DDT decline in response to bans and restrictions, polluted sites such as abandoned settlements, mining areas and military installations become increasingly important contributors to Arctic contamination (NCP, 2003; NCP, 2013). These sources have often transgressed from being local point sources to becoming extended diffuse sources, having been allowed to spread over large areas including soil, ground water, water sheds, sediments and biota for decades. These diffuse sources are beyond bans and the risks for human and environmental exposure and contamination must therefore be assessed and appropriate measures taken.

Today increasing attention is also being paid to “new contaminants” or contaminants of emerging concern (CECs). These chemicals are currently in use and local sources therefore become highly relevant in the Arctic in relation to long range transport (NCP, 2013). CECs include, e.g. different forms of second generation flame retardants (Brominated flame retardants - BFR, Organophosphorus flame retardants - OPFR), plasticisers (e.g. phthalates, bisphenols), surface or material modifying compounds (perfluorinated alkyl substances - PFAS, PFOA, chloroparaffins - SCCP), pharmaceuticals (e.g. antibiotics, antidepressants and painkillers) and contaminants included in personal care products (e.g. siloxanes) and microplastics with associated pollutants (GESAMP, 2015; NCP, 2013). Important environmental sources of these unregulated compounds are, e.g. garbage dumps, municipal and hospital sewage systems, air and heliports.

The aim of this report is to; 1) provide a brief review of polluted sites and their sources in Svalbard using accessible information, 2) to describe current available remediation options, and 3) to provide guidance on future actions regarding polluted sites in Svalbard. Examples of remediation actions carried out in the Arctic and Antarctic regions form the base of the discussion. It is important to bear in mind that the pollution we describe is what we currently understand as being important to measure. New chemicals are introduced on the market at higher rates than they are being assessed for possible environmental effects.

1 CHARACTERISTICS OF RELEVANT LOCAL CONTAMINATION SOURCES

1.1 MINING AND MINING DUMPSITES

Coal extraction dominates the mining activities in Svalbard. The environmental consequences arising from coal mining voids and wastes can be summarized under five major headings: air pollution, fire hazards, ground deformation, water pollution, and water resource depletion (Tiwary, 2001; Younger, 2004). Water pollution of course results from contaminants leaching or being swept away with winds associated with particles from coal piles and mining dumps. The main types of pollution from the coal mining activities are;

- Heavy metals (Fe, Cu, Mn, Cd, As, Ni and Hg)
- PAHs (mainly alkylated forms) associated with the coal itself
- Acid drainage from coal, pyrite (FeS₂), siderite, and ankerite
- Chemicals associated with machinery, e.g. PCB
- Chemicals associated with fire prevention and firefighting, e.g. PFC, PCB
- Chemicals associated with explosives, e.g. nitroglycerin
- Fuels including various kinds of petroleum products

In Svalbard, waste from coal mining has mainly been deposited in uncovered piles placed adjacent to the mining voids (Hansen et al, 1998). If the sulphur content of the coal is high, sulphuric acid production in the piles will lead to metal dissociation and accumulation in the acidic solution. This solution will then leach out of the pile into the surrounding environment where it can be potentially harmful. This has been observed for most of the coal piles in Svalbard (Breedveld et al, 1999a; Breedveld et al, 1999c). It is during the spring thaw that the pH is the lowest and the concentration of metals is the highest in coal pile drainage water, likely resulting from accumulation of weathering products inside the pile during wintertime (Søndergaard et al, 2007). Elberling et al. (2007) report that the core of a coal waste pile in Svalbard keeps a temperature of ~5 °C year around, which allows for continuation of the chemical processes leading to sulphuric acid production and subsequent dissolution of metals. At the time of the spring thaw, the active layer above the permafrost is still frozen and thus presents a barrier to the meltwater. Therefore, most of the meltwater with its low pH and elevated metal concentration will be released as surface runoff, potentially affecting soil, flora and fauna (Askaer et al, 2008; Elberling et al, 2007).

Piled unburnt or native coal can contain large amounts of PAHs. The limited published quantitative data available show that PAH concentrations can vary between 1 and 2500 mg kg⁻¹ (43 PAHs including the EPA 16PAH and alkylated forms) in unburnt coal depending on quality and origin (Achten & Hofmann, 2009). These numbers correspond to EPA 16PAH concentrations from below 1 to 160 mg kg⁻¹. The PAHs are mostly associated with particles and will be transferred wherever coal pile dust moves. PAHs derived from coal dust have been recorded in soils, lakes, marine waters and sediments in Svalbard (Breedveld et al, 1999a; Breedveld et al, 1999b; Breedveld et al, 1999c). Very little is known about the environmental impact of unburnt coal (Achten & Hofmann, 2009). Furthermore, the dumpsites associated

with coal mines have also served as dumpsites for larger debris, used up machinery and old fuel tanks (iron bars, broken electrical and mechanical machinery, containers et c). The dumpsites may thus act as sources of the variety of chemical compounds used during the decades they have existed.

1.2 GARBAGE DUMPSITES AND LANDFILLS

There is a difference between old and new (established in the past 15 years) dumpsites in that regulations regarding recycling of materials and collection and shipping of hazardous waste to mainland treatment facilities have been implemented (The Government of Norway, 2001; The Government of Norway, 2002). This means that contamination issues are more diverse and can be more severe at old dumpsites and landfills. An important concern with Arctic dumpsites is the presence of organic materials causing internal heat production, when microbially degraded, and subsequent melting of the barrier-like permafrost layer (Løtveit, 2012). The main types of contamination that may be found in leachate from landfills or dumpsites include (Kjeldsen et al, 2002; Løtveit, 2012);

- Biological material (dissolved and particulate organic matter)
- Inorganic macro-components, e.g. Ca, Mg, Na, K, chloride, sulphate, borate, carbonate and ammonium
- Heavy metals, e.g. Cr, Cd, Cu, Pb, Ni, Hg, As and Zn
- All kinds of organic contaminants originating from household or industrial materials or chemicals, e.g. flame retardants, plasticisers, pesticides, aromatic hydrocarbons, phenol, chlorinated aliphatics and PPCPs
- Microplastics
- Pathogenic bacteria

The knowledge regarding environmental contamination from dumpsites in the Arctic is limited, but issues are likely to resemble those concerning dumpsites in temperate areas. However, lower temperatures and the lack of sunlight during the winter months will influence biological and chemical degradation processes occurring within the dump. Furthermore, the degree of management will differ from settlement to settlement across the Arctic. Importantly, logistic difficulties regarding transportation of garbage from Arctic settlements has traditionally involved open air burning of garbage at the dumps. Unregulated burning of garbage results in the formation and release of various combustion related contaminants, e.g. VOCs, pyrogenic PAHs and dioxins, which will be released into the surrounding air and also accumulate at and around the dumpsite.

1.3 SEWAGE

Sewage treatment is generally lacking in the Arctic, and untreated sewage is thus released directly into pristine marine environments (Gunnarsdóttir et al, 2013a). This is the case in all settlements in Svalbard, except for a small older treatment plant at the Polish research station in Hornsund and a sewage treatment system installed in 2015 in Ny-Ålesund. Here the resulting sludge is a potential source of pollution and must be disposed of accordingly. Release of untreated sewage is one of the most important unregulated local pollution sources

in the Arctic. Sewage discharge is traditionally associated with causing eutrophication problems in receiving waters, inducing intensified algal blooms, anoxic sediments and impaired benthic communities (Rosenberg et al, 1986). However, in the oligotrophic coastal waters of the Arctic, organic matter and nutrient addition often have a stimulatory effect leading to a localized richer benthic fauna instead of dead anoxic seafloors in association with discharge points (Dahl, 2007). The main concern is instead release of contaminants associated with different types of materials and personal care products (additives), pharmaceuticals, microplastics, as well as pathogens and resistant bacteria associated with human excrements (Chaves-Barquero et al, 2016; Gunnarsdóttir et al, 2013b; Jensen et al, 2013; Magnusson et al, 2016). If industrial and hospital sewage is connected to the municipal sewage system, chemicals used in the specific operations, e.g. disinfectants, solvents, flame retardants, biocides, should be added to the list of sewage associated pollutants.

1.4 AIRPORTS AND HELIPOINTS

Everyday activities at airports include several polluting activities, e.g. combustion of aviation fuels, cleaning of aircrafts and ground vehicles, aircraft maintenance and repair, fuelling operations, engine test cell operations, de/anti-icing operations, ground vehicle maintenance, and removal of snow, weed and vegetation from the airport apron. To maintain these operations airports use a wide variety of chemicals thus resulting in the environmental release of, e.g. cationic, anionic and non-ionic detergents, formaldehyde, phenols, PAHs, PCBs, pesticides and heavy metals, together with runoff waters (Sulej et al, 2011; Sulej et al, 2012). Most pollution-related water quality problems at airports occur during wintertime, since a colder climate requires a greater use of de-icing salts, detergents and other compounds. Arctic airports are thus particularly exposed to this type of pollution issues (Sulej et al, 2012).

Airports also need preparedness for accidental fires, and part of the airport therefore functions as a fire station. Firefighting training sites are often located in the vicinity of the airports. These training sites have received extensive recent attention, since continuous use of firefighting foams has led to serious contamination of soil, ground water and watersheds with PFCs such as PFOS and PFOA released with runoff water (Nordskog, 2012). PFCs are suspected carcinogens with persistent, bioaccumulating and biomagnifying properties.

2 CONTAMINATED LAND SITES IN SVALBARD

In 1998 the Norwegian Environment Agency (at that time “Statens forureningstilsyn”) and the Governor of Svalbard made a joint effort to identify and map hazardous waste landfills, contaminated ground areas and remains/artefacts of earlier activities in Svalbard including at the islands of Bjørnøya and Hopen (Fig. 1). The investigation was an initial survey based on visual on-site inspections combined with existing knowledge of contamination sources. This survey covered sites of current and historical industrial activities in, e.g. Longyearbyen, Barentsburg, Pyramiden, Ny-Ålesund, Svea and a number of sites outside the main settlements (Hansen et al, 1998). The survey formed a basis for further investigations of sites of particular concern (corresponding to approximately a level 2 risk assessment) in

Longyearbyen (Breedveld et al, 1999a; Breedveld et al, 1999c), Barentsburg, Pyramiden (Breedveld et al, 1999d) and Ny-Ålesund (Breedveld et al, 1999b).

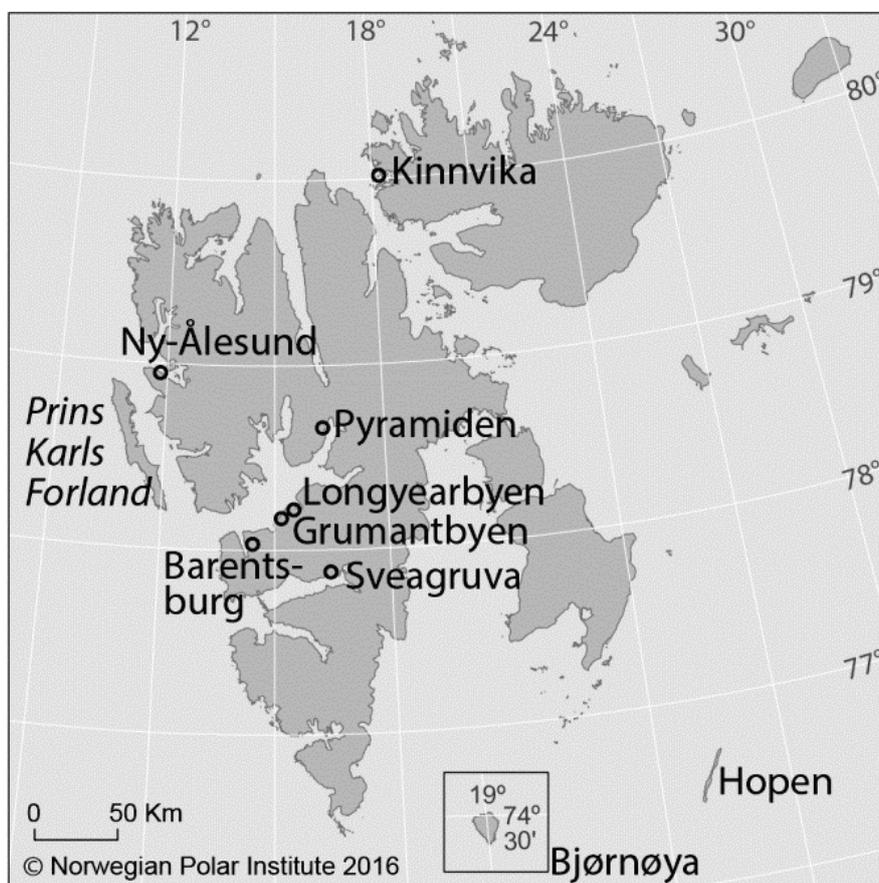


Figure 1. Map of Svalbard with main settlements and islands.

The investigations by Breedveld et al. (1999a; 1999b; 1999c; 1999d) all had a similar design and included chemical analyses of heavy metals (Cr, Ni, Cu, Zn, Cd, Pb, As, Hg, Al, Fe), anions in water including nutrients and sulphate, PAHs (EPA 16PAH), PCB, BTEX and hydrocarbons primarily in soils, freshwater sources and sediments. Collectively the investigations show clear impacts of mining and associated activities in all areas with possible effects on both humans and ecosystems. Further investigations and remedial actions were suggested in most cases and partly followed up in Svea (Breedveld & Skedsmo, 2000b), Ny-Ålesund (Breedveld & Skedsmo, 2000c; Børresen, 2003), Longyearbyen (Breedveld & Skedsmo, 2000a) and Russian settlements (Børresen & Sørli, 2002). The investigations showed various degrees of contamination from mining activities (acid and heavy metal drainage), fuel storages (petroleum), and garbage dumpsites (PAH, PCB, pesticides, heavy metals etc) at all settlements. In the initial survey by Hansen et al (1998), a number of sites outside the settlements were also identified as being of concern in terms of soil contamination. These included former petroleum exploration sites, and attempts to further investigate and determine possible environmental risks at these sites were made (Altin, 2000; Sørli, 1999). Conclusions regarding contamination levels and how to remediate contaminated soil were,

however, obscured by the largely inadequate or altogether lacking documentation of these industrial activities. The current state of these sites is unclear.

Between 2007 and 2009 extensive investigations were performed in order to determine the extent of PCB contamination in settlements in Svalbard, and samples were collected from soil, house paint, concrete, oils from various types of equipment etc (Eggen & Ottesen, 2008; Jartun et al, 2010; Jartun et al, 2007). Very high PCB concentrations were found in building materials, electrical parts (capacitors) and surface soils at Barentsburg and Pyramiden and the process of removing the contaminated materials has started. During an investigation in 2007-2008 high concentrations of PCBs and PAHs were detected in surface soils around the abandoned research station at Kinnvika, Nordaustlandet (Harris, 2008). When revisiting the site for supplementary sampling and marine investigations, PCBs and PAHs were detected but concentrations were determined to be much lower in soil than previously reported (Evenset & Christensen, 2012), thus requiring no further assessments or remedial actions (Evenset & Christensen, 2011).

The Norwegian Environment Agency holds a database on contaminated ground sites in Norway, <http://grunn.miljodirektoratet.no/>. This database is updated when new contaminated sites or remediation actions are reported to the agency and the database is therefore dynamic, but not complete. The database provides an overview of contaminated ground, dumpsites, freshwater sediments, abandoned military sites and other contaminated industrial or recreational sites. Extracts from this database are presented in the following settlement-based descriptions below. The ambition of this report is to provide a brief overview of important contaminated sites in Svalbard based on accessible information. For details the reader is kindly referred to the cited literature.

2.1 LONGYEARBYEN

Longyearbyen is the largest settlement and the administrative centre of Svalbard. The settlement was built on the coal mining industry but today education, research and tourism are the most important sources of employment. The resident population is just above 2000, but increases drastically during tourist seasons reaching over 130 000 “guest nights” in 2015 (<http://www.mosj.no/no/pavirkning/ferdsel/overnattinger-longyearbyen.html>). The resident population and number of visitors show a steady increase (Bjørnsen & Johansen, 2014). The area hosts a very high terrestrial biological diversity compared to other Arctic sites at the same latitude (Hagen & Prestø, 2007). Several of the species are either rare or red-listed (<http://www.npolar.no/no/tema/naturmangfold/land/dyreliv/>, <http://www.npolar.no/no/tema/naturmangfold/land/vegetasjon/>, <http://www.artsportalen.artsdatabanken.no/>).

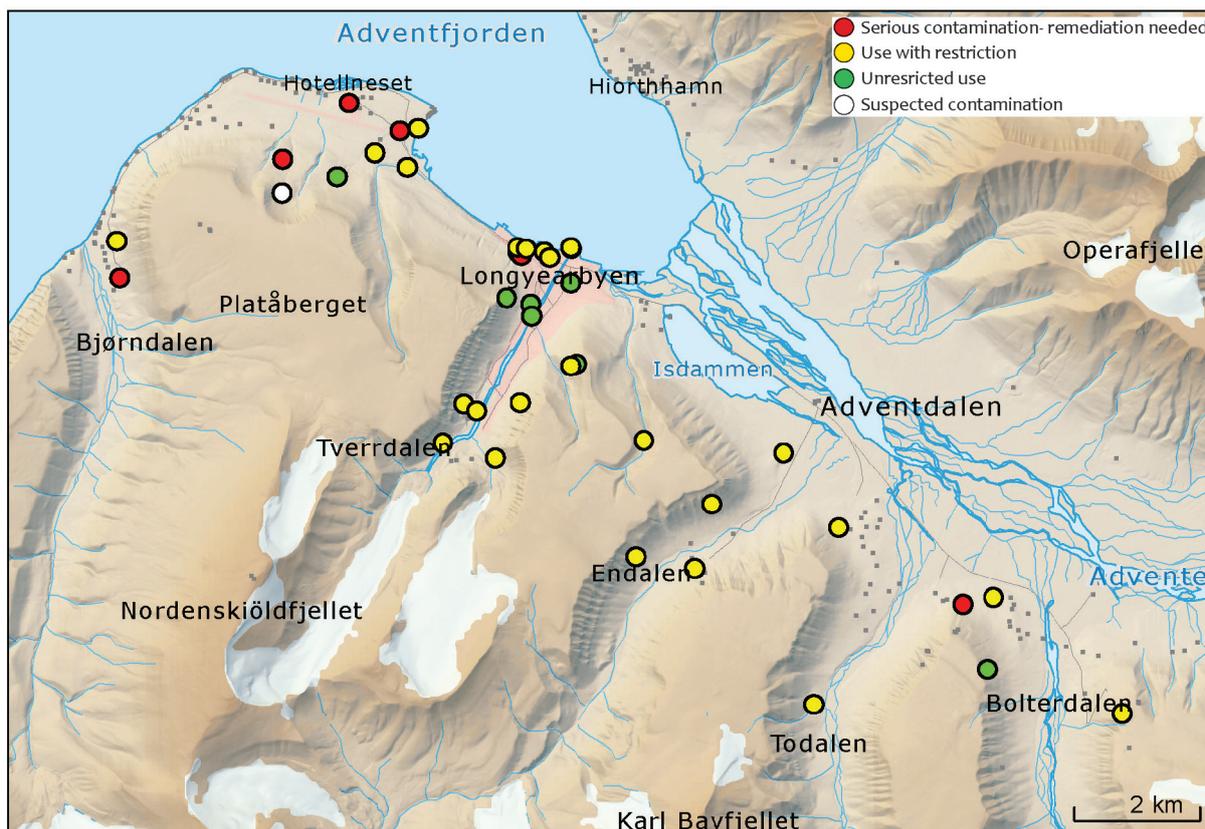


Figure 2. Longyearbyen with reported contaminated sites, <http://grunn.miljodirektoratet.no/>.

2.1.1 Mining

Longyearbyen has a history of coal mining but the only active mine today is Mine 7, with an annual coal production of 60 000 tonnes used partly for local energy and heating (Evenset, 2013). Coal dust is omnipresent in Longyearbyen soil and sediments and is likely to contribute to elevated background PAH concentrations in this area (Breedveld et al, 1999a). Runoff from the closed mines are characterized by acid drainage and high to very high contents of heavy metals such as Fe, Ni, Cu and As, while PCB pollution is negligible. The runoff drains into the Longyearrelva River flowing into the Adventfjord. Severe diesel oil contamination was discovered in 1999 at Sverdrupbyen at the far end of the Longyeardalen valley, risking to contaminate the groundwater (Breedveld et al, 1999c)(Fig. 2).

2.1.2 Dumpsites and sewage

Handling of garbage and sewage is an important part of the infrastructure. Today most of the garbage and waste from Longyearbyen is sent to mainland Norway for incineration (S. Reiten, Governor of Svalbard, pers. comm.). Garbage, which is disposed of at the main garbage dumpsite in Adventdalen, consists mainly of inert materials such as glass, plaster boards, steel, concrete, isolation materials and plastic (Lyche & Nedland, 2012). Solid waste and ash from the coal fired power station are also currently deposited here, and may contain traces of heavy metals, PAHs and dioxins. Hazardous material has likely been deposited at this dumpsite in earlier days without having been recorded (S. Reiten, Governor of Svalbard, pers. comm.). Løtveit (2012) detected heavy metal concentrations above the restricted limits in leachate from the Adventdalen dumpsite. Most of the landfills in Longyearbyen rest on old garbage,

and old dumpsites are located along the shores at “Sjøskrenten”, and from the marina “Småbåtshavna” towards the town dock “Bykaia” and the old dock “Gammelkaia” (S. Reiten, Governor of Svalbard, pers. comm.). Breedveld et al. (Breedveld et al, 1999a) detected high concentrations of petroleum-related PAHs at one of these dumpsites, and the high pH and conductivity measured in leachate indicated penetration of seawater into the dump itself. The current state of these sites is unclear.

Sewage from the municipality and the airport is collected and released untreated into the Adventfjord recipient at approximately 60 m depth 2 km off the coast. Before 2008 the town had four sewage outlets; (town harbour (Bykaia), power station (Energiverket), outside the fire station, and main outlet at the seashore (Sjøskrenten), which were then merged with the present outlet. In 2011 food waste became allowed to be released through the sewage system. The annual sewage discharge is approximately 170 000 m³ including 100 tonnes of food waste (Dahl, 2007; Sjöberg et al, 2014). Vasskog et al. (2008) measured antidepressant pharmaceuticals in sewage discharge from Tromsø (population of 73 480 in 2016 (Tromsø kommune)) and Longyearbyen, concluding that trace levels were detectable at both sites. Concentrations were higher at the sewage outlet in Adventfjorden than in Tromsøsund despite the substantially smaller population of Longyearbyen. This was attributed to ocean current conditions at the respective sites where the more stagnant Adventfjord water allows for local accumulation of released pharmaceuticals. Sediment investigations in association with the sewage outlet have also confirmed the release of PFC (Evenset et al, 2009; Olsson, 2016), OPFR and PBDE (Olsson, 2016).

2.1.3 Airport

The Longyearbyen airport is situated on the slope of a moraine. Groundwater drains from the side of the moraine into the Adventfjord. The airport collects part of the drainage water from the working areas and releases it at 18 m depth in the Adventfjord (Fig. 3). A large part of the runoff from the airstrip and working areas does, however, drain directly into the Adventfjord lagoons “Laguner” (Fig. 3-A) and into the fjord itself. The lagoons are frequented by migrating seabirds. Breedveld et al (1999c) reported severe petroleum contamination of soil at the old firefighting training site (Fig. 3-D). This site has mainly been used as an airport firefighting training site. Surface soils also contained degradation products of pesticides (DDT and endosulfan) and PCB. The groundwater at the site was also strongly contaminated with petroleum. The airport has recently been investigated regarding their use and release of contaminating chemicals with particular recent focus on PFCs (Norconsult AS, 2015; Pengerud & Kvisle, 2016; Rudolph-Lund, 2012). PFCs above restricted limits were detected at the old firefighting training site, spreading in an easterly direction. Likewise were PFOS levels exceeding environmental restriction levels at the new firefighting training site, with runoff water containing mainly PFOS (5.5 µg l⁻¹) (Rudolph-Lund, 2012). The most recent environmental assessment of the airport focused on contaminants associated with water runoff draining into the lagoons and Adventfjord (Pengerud & Kvisle, 2016). The investigation showed elevated concentrations of heavy metals, BTEX, THC and PFAS in soil and water samples, indicating that actions should at least be taken to protect adjacent watersheds.



Figure 3. Radar image of the Longyearbyen air- and heliport (top) with some installations and sites associated with handling or storage of hazardous materials indicated: A) lagoons, B) source horizon, C) snow deposit east, D) old firefighting training site, E) active firefighting training site, F) snow deposit west for helicopter hangar and apron, and G) drainage pipe. Radar image courtesy the Norwegian Polar Institute. Bottom map showing land runoff water drainage around the Longyearbyen Airport (Pengerud & Kvisle, 2016).

2.2 NY-ÅLESUND

Ny-Ålesund was founded as a mining settlement by Kings Bay AS in 1917 and terminated as such in 1963. It is now run exclusively as an international research facility, hosting ~25 persons in winter and ~200 in the summer. The community of Ny-Ålesund, including the research facilities and infrastructure, is operated by Kings Bay AS under the Norwegian Ministry of Climate and Environment. Problematic sites in terms of contamination are the old

landfill and dumpsites in Thiisbukta, the fuel storage in the settlement, the closed mining areas, the airport and possibly the sewage outlet (Breedveld & Skedsmo, 2000c; Breedveld et al, 1999b; Børresen, 2003; Skei, 1994) (Fig. 4). In an extensive survey of PCBs in Svalbard, 16 samples were collected at strategic locations in Ny-Ålesund and only one showed traces of PCB contamination (Jartun et al, 2010).

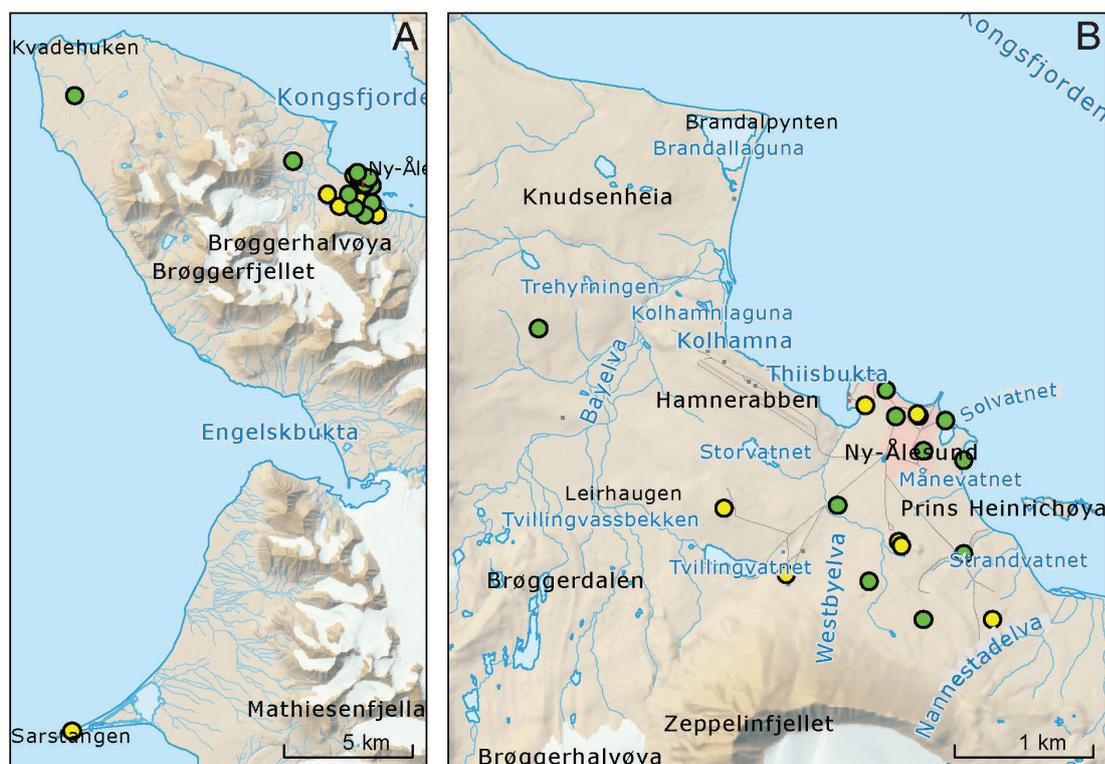


Figure 4. Map of A) Brøggerhalvøya and vicinity and B) Ny-Ålesund showing reported contaminated sites as coloured circles, <http://grunn.miljodirektoratet.no/>. For figure legend see Fig. 2.

2.2.1 Mining

Due to extensive coal mining activities, coal dust is expected to be omnipresent in soil and watersheds, entailing elevated - but not high - background PAH concentrations. The mining sites show elevated acid, metal and PAH drainage concentrations but levels are below restriction limits. The drinking water reservoir “Tvillingvannet” lies downslope from an old mining site, and although only slightly elevated metal concentrations were detected in sediments from the reservoir, sheltering from any runoff was advised (Børresen, 2003). It is unclear to what extent these recommendations have been followed through. At Mining shaft 3 above “Zeppelinhamna” corroding containers containing oil with PCB were observed by Breedveld et al. (1999d). It is unclear if, but likely that they have been removed.

2.2.2 Dumpsites and sewage

The old dumpsite at Thiisbukta constitutes one of the more extensive contamination sources in Ny-Ålesund (Breedveld et al, 1999b; Børresen, 2003; Skei, 1994). High concentrations of mineral oil, PAH (40 mg kg^{-1} DW soil), PCB ($135 \text{ } \mu\text{g kg}^{-1}$ DW soil) and pesticides ($10 \text{ } \mu\text{g kg}^{-1}$ DW soil) were detected here including traces of heavy metals and Hg (Breedveld et al,

1999b; Skei, 1994). Elevated concentrations of PCB and PAH have also been detected in Thiisbukta sediments pointing to the dumpsite as source (Skei, 1994). The old sewage pipe ran across the bird sanctuary and ended on the shore next to the small lake “Solvatnet”. The current sewage outlet is located at ~ 3 m depth in the fjord, 30-40 m from the shore between Solvatnet and the boat pier. In 2015 a sewage treatment system (Klaro renseanlegg Norge AS) with combined nitrification-denitrification was installed in Ny-Ålesund (Kings Bay pers. comm.). The resulting concentrated sewage sludge is dried on site and shipped to the mainland for destruction.

2.2.3 Airport

To the best of our knowledge there is currently no overview of chemical use or spills from the airport in Ny-Ålesund. In 2016 the governor of Svalbard requested information from Kings Bay specifically regarding the use of firefighting foams (Solvår Reiten at The Governor of Svalbard pers. comm.). PFC containing firefighting foams have likely been used here and perhaps in conjunction with the mines. It is, however, unclear to what extent and where this activity has taken place.

2.2.4 Fuel storage area

The fuel storage is located between the main buildings and the harbour and it is situated on a sand and gravel fill. Numerous spills have been recorded and in 1985 the oil pipe broke causing a spill of 88 m³ oil. The area drains into the small lake “Solvatnet “ located close to the shore in the bird sanctuary (Hansen et al, 1998). Elevated PAH concentrations have been reported at Solvatnet. The fuel storage site and surrounding area have been reported to be strongly affected by petroleum contamination and investigations in 1998 describe oily water percolating up from newly dug pits in the ground (Breedveld et al, 1999b). It is unclear whether the area has been remediated according to recommendations given by Børresen (2003). Today the area around the fuel storage containers includes a designated oil spillage dam.

2.3 BARENTSBURG & PYRAMIDEN

Barentsburg (active coal mine and town harbouring 4-500 inhabitants including children) and Pyramiden (currently closed down and principally abandoned) are, together with Longyearbyen, the most extensive coal mining settlements in Svalbard. Several studies have been conducted to determine environmental pollution and risks at these sites. The investigations embrace studies of the mining sites, dumpsites, building materials, soil, watersheds, marine waters, sediments etc (e.g. Breedveld et al, 1999d; Børresen & Sørli, 2002; Evenset & Christensen, 2009; Evenset et al, 2009; Hansen et al, 1998; Jartun et al, 2010; Jartun et al, 2007) (Fig. 5).

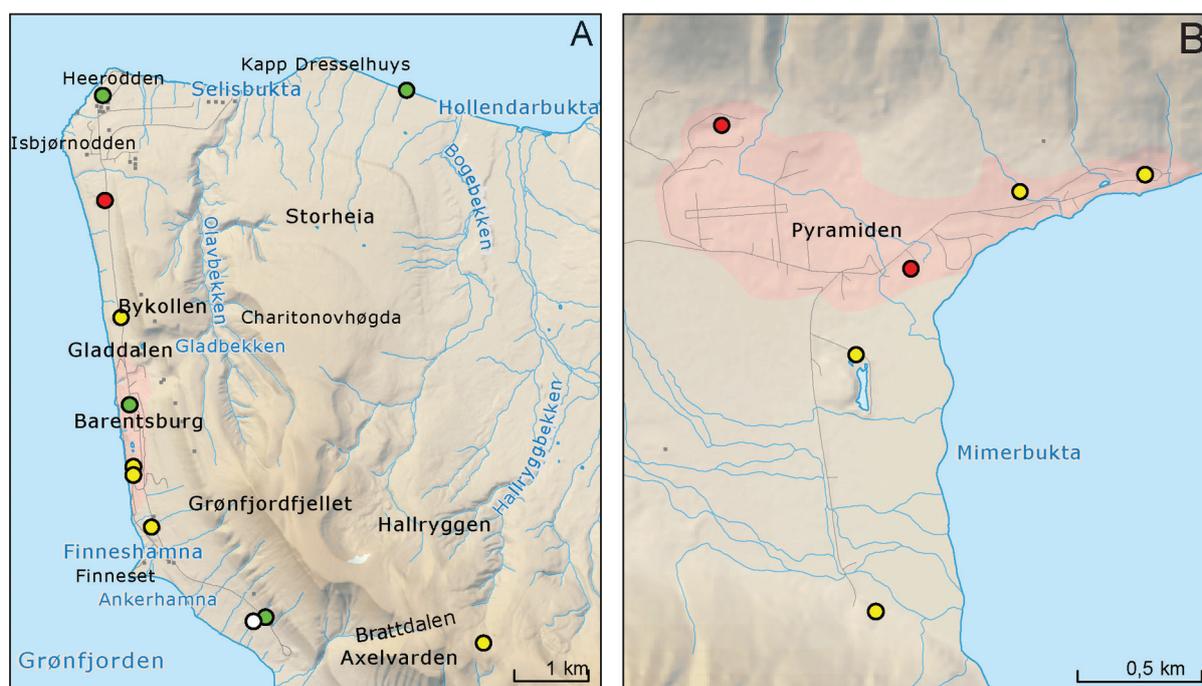


Figure 5. Map of A) Barentsburg and B) Pyramiden showing reported contaminated sites as coloured circles, <http://grunn.miljodirektoratet.no/>. For figure legend see Fig. 2.

Areas around fuel storages in Pyramiden and at the heliport in Barentsburg have been found to be heavily petroleum contaminated, to the extent that adjacent watersheds were reported to be impacted (Breedveld et al, 1999d; Børresen & Sørli, 2002). The dumpsites at both settlements likely contain debris of particular concern since PCB has been detected here along with heavy metals, BTEX and PAHs. Garbage has repeatedly been burnt at the dumpsites, which has likely contributed to thawing and subsequent release of these contaminants. Leachates were otherwise found to be surprisingly low in contamination, which was attributed to the fact that the dumps stay frozen year around (Breedveld et al, 1999d; Børresen & Sørli, 2002).

All surface soil in Barentsburg and Pyramiden has been reported to contain PCB (Jartun et al, 2010; Jartun et al, 2007). The median PCB₇ concentrations in soil detected in Barentsburg (0.268 mg kg^{-1} DW soil) and Pyramiden (0.172 mg kg^{-1} DW soil) were 40-60 times higher than those found in similar surveys from the Norwegian towns Oslo, Bergen, Trondheim, Harstad and Tromsø. High concentrations of PCB₇ were also found in house paint in Barentsburg (up to 3520 mg kg^{-1}) and Pyramiden (up to 1290 mg kg^{-1}). Small capacitors collected from electrical installations in Barentsburg and Pyramiden contained concentrations of up to $114000 \text{ mg PCB}_7 \text{ kg}^{-1}$. Similar investigations have been carried out by Russian scientists with particular focus on Barentsburg (NPO Typhoon, 2008). Inter-calibration between Russian and Norwegian measurements shows satisfying concurrence (Evenset & Ottesen, 2009). Measures have been taken to remove PCB hazards but it is unclear to what extent. Unmetabolized DDT was found both in watersheds and marine sediments around Barentsburg indicating an active DDT source (Evenset, 2010). Recent marine sediment investigations in the Grønfjord outside Barentsburg further confirm release of PFC, OPFR and PBDE (Olsson, 2016).

2.4 GRUMANT & COLESBUKTA

The Russian coal mining areas at Grumant and Colesbukta were established in the early 1900s. A small railway transported coal from the Grumant settlement to Colesbukta for further shipping. Coal mining activities were terminated in the 1960s. PCB has been found in paint (up to 160 mg PCB₇ kg⁻¹) and surface soil (average 0.365 mg PCB₇ kg⁻¹) at intermediate levels compared to those found in Longyearbyen and Barentsburg (Jartun et al, 2010). The area around the oil depot in Colesbukta was found to be heavily contaminated with petroleum (Breedveld et al, 1999d) (Fig. 6). A thorough risk assessment with a remediation plan was performed mainly concerning extraction of oil from the two landlocked boat hulls, and removal of the hulls themselves, which have been used for petroleum storage (Havik & Nag, 2009). It is unclear whether the suggested remediation actions have been performed.



Figure 6. Map of Grumant and Colesbukta showing reported contaminated sites as coloured circles, <http://grunn.miljodirektoratet.no/>. For figure legend see Fig. 2.

2.5 SVEA

Svea is a small, recently closed mining site established in 1917. The mine is owned by Store Norske Spitsbergen Grubekompani and can only be reached by water or air, and therefore has its own airstrip. The whole area around Svea is characterized by coal mining activity and coal dust is omnipresent. Aside from the mining itself, fuel storage and dumpsites constitute important contamination sources (Fig. 7). The old dumpsite is located by the airstrip and the new dumpsite (since 1970s) is located at Kapp Amsterdam. The sites are both situated on bare ground. The Kapp Amsterdam dumpsite is protected by gravel barriers inside which water accumulates. The water is subsequently led into the fjord through an opening in the barrier. Household and industrial waste, as well as debris of particular concern, has been dumped here. Intermittent burning of waste has also occurred. Leachate from the dumps has been shown to contain elevated heavy metal, PCB and PAH concentrations (Breedveld & Skedsmo, 2000b).

However, in 2008 paint and soil samples were collected and analysed for PCBs, showing no PCB contamination of concern in any sample (Jartun et al, 2010).

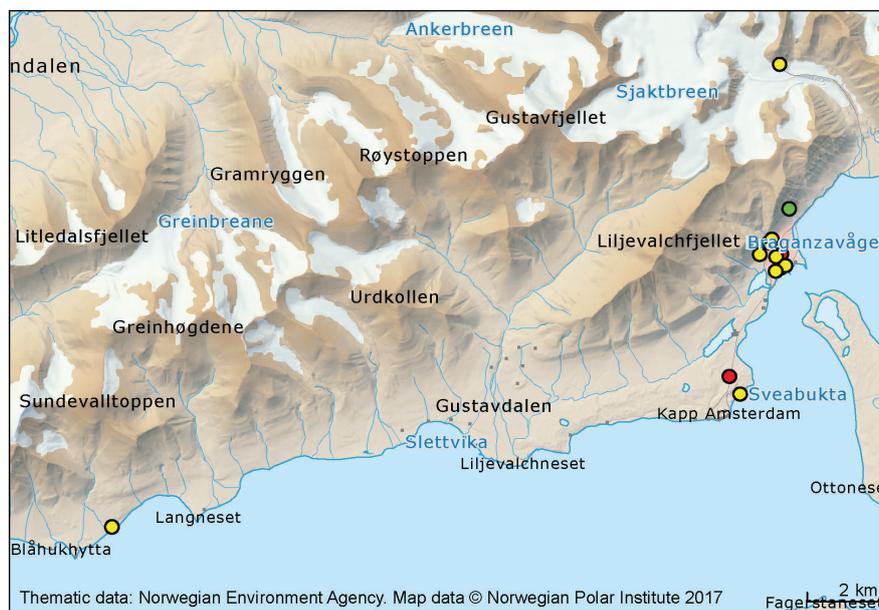


Figure 7. Map of Svea showing reported contaminated sites as coloured circles, <http://grunn.miljodirektoratet.no/>. For figure legend see Fig. 2.

2.6 SITES OUTSIDE SETTLEMENTS

A number of sites outside of the larger settlements are relevant when it comes to soil pollution. These sites include weather/radio stations, smaller mineral and coal mines and oil drilling sites. The two islands Hopen and Bjørnøya, located in the Barents Sea south and east of Spitsbergen, each host meteorological stations run by the Norwegian Meteorological Institute. The islands are also important landing, bunker and refuelling sites for, e.g. rescue helicopters. These activities naturally involve fuel storage and supply facilities, power generators, sewage discharge and dumpsites as possible contamination sources. Both Hopen and Bjørnøya (not including the area around the meteorological stations) are now nature reserves.

2.6.1 Hopen, Bjørnøya and Signehamna

During WW2 the German Air Force established a meteorological station on the east coast of Hopen approximately 7 km from the south cape. After the war the Norwegian Meteorological Institute took over the responsibility of the station. In the early 1970s exploration drilling for oil was conducted at two sites on Hopen; Hopen 1 in the south (1971) and Hopen 2 (1973) in the north (Fig. 8). Oil-discoveries were not grand enough to support further oil or gas extraction and the sites were abandoned.

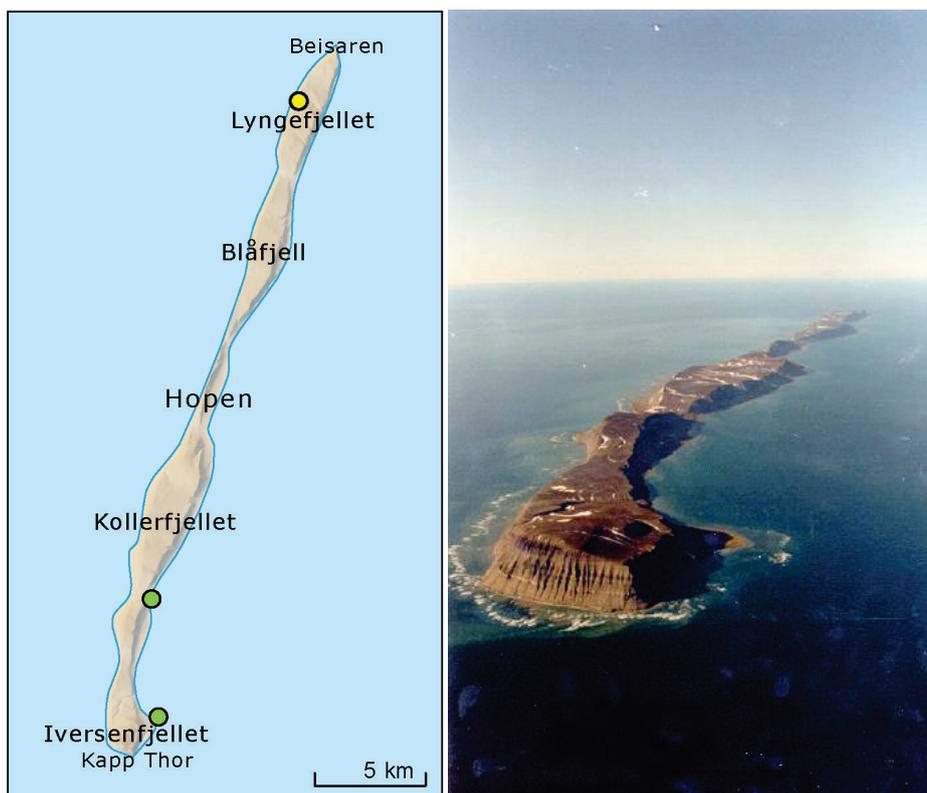


Figure 8. Map and photograph of the island Hopen east of the southern tip of Spitsbergen. Map showing reported contaminated sites as coloured circles, <http://grunn.miljodirektoratet.no/>. For figure legend see Fig. 2. Photograph from the Norwegian Meteorological Institute <http://met.no/Hopen.9UFRjU2F.ips>.

Bjørnøya has been subject to both mineral and coal mining in the early 1900s. Barite and lead glance was extracted during 1925-30 at Gruben and Blyhatten in the south, while coal was extracted during 1916-25 in Tunheim in the north. The meteorological station on Bjørnøya was established already 1918 and is located on the northern coast. One of the most unique places in terms of contamination on Bjørnøya is lake Ellasjøen, which contains unusually high levels of PCB mainly originating from guano provided by migrating birds (Evenset et al, 2007; Evenset et al, 2004). In 2008 Hopen, Bjørnøya and Hornsund were investigated for possible PCB contamination (Eggen & Ottesen, 2008). PCB contamination was negligible, aside from elevated PCB concentrations found in house paint and selected soil samples collected at the Meteorological station on Bjørnøya. A meteorological station was also established in Signehamna/Signedalen in Krossfjorden by the German Air Force during WW2. Soil contamination is suspected to be present at this site but has, to the best of our knowledge, not been further investigated.

2.6.2 Petroleum exploration and oil drilling sites

There are in total 20 petroleum exploration or oil drilling sites in Svalbard mostly located on the west coast of Spitsbergen, but also on the Edgeøya and Hopen islands (Table 1) (Johannesen & Stenløkk, 2004). Oil prospecting in Svalbard lasted for 30 years between 1963 and 1994. There are no such activities in Svalbard today.

Table 1. Overview of the petroleum exploration sites/ boreholes in Svalbard. Source: The Directorate of Mining with the Commissioner of Mines at Svalbard.

Exploration site/ borehole	Operator/ Owner	Time	Depth (m)
Green Harbour	Northern Petroleum Company	1920	4
Grøn fjorden 1	Norsk Polar Navigasjon A/S	1963-67	972
Ishøgda 1	Texaco/ Caltex- group	1965-1966	3304
Bellsund 1	Norsk Polar Navigasjon A/S	1967-1981	405
Hopen 1	Forasol/ Fina-group	1971	908
Raddedalen	Total/ Caltex-group	1972	2823
Plurdalen	Fina/ Fina-group	1972	2351
Kvadehuken 1	Terratest A/S/ Norsk Polar Navigasjon A/S	1972-1973	479
Hopen 2	Westburne Int. Ltd./Fina-group	1973	2840
Kvadehuken 2	Terratest A/S/ Norsk Polar Navigasjon A/S	1973-1974	394
Sarstangen	Terratest A/S/ Norsk Polar Navigasjon A/S	1974	1114
Colesbukta	Trust Arktikugol	1974-1975	3180
Tromsøbreen 1	Terratest A/S/ Norsk Polar Navigasjon A/S	1976-1977	990
Tromsøbreen 2	Deutag/ Tundra A/S and partners	1987-1988	2337
Vassdalen 1	Trust Arktikugol	1985-1987	2481
Vassdalen 2	Trust Arktikugol	1988-1989	2315
Reindalspasset	Aker-Deutag/ Hydro-SNSK	1991	2315
Petuniabukta 1	Trust Arktikugol	1992	?
Petuniabukta 2	Trust Arktikugol	1992	?
Kapp Laila	SNSK/ SNSK-Hydro-Trust Trust Arktikugol	1994	504

Documentation regarding, e.g. site descriptions, working routines, chemical use and possible pollution incidents is highly insufficient or altogether lacking from these historical industrial sites (Altin, 2000; Hansen et al, 1998; Sørli, 1999). Existing information, e.g. about the drilling sites on Edgeøya and Kvadehuken is largely based on witness statements from people who used to work there when the sites were operative (Sørli, 1999). Some of the sites were visually inspected (corresponding to a simplified Level 1 risk assessment without soil measurements) in 1998 (Hansen et al, 1998). This initial inspection was supplemented by an environmental risk assessment of all sites in 2000 ordered by The Governor of Svalbard (Altin, 2000). The risk assessment performed by Altin (2000) was based on existing documentation and previous experience from risks associated with the use of oil drilling chemicals. The main conclusions were that (*translated from Norwegian*):

- The available data were so scarce, and information about the extent and exact location of the drilling operations of such kind, that contamination of the sites could not be excluded.
- The way drill cuttings and fluids had been handled and disposed of was likely to cause contamination.

Specific measures to further investigate, remediate and follow up possible contamination were suggested for the oil drilling sites; Grøn fjorden 1, Sarstangen, Tromsøbreen 1, Tromsøbreen 2 (Haketangen), Ishøgda, Hopen 2, Raddedalen, Plurdalen, Colesbukta, Vassdalen 2 & 3 and Reindalspasset 1. With the currently accessible documentation it is unclear to what extent

these recommendations have been followed through and it is consequently not possible to report on the present extent of soil contamination at these former oil drilling sites. It is further important to note that the mentioned environmental risk assessment (Altin, 2000) only considered contamination related to former petroleum activities. The petroleum exploration sites also hosted other facilities such as air strips with up to 40 landings of Hercules type air planes (Sørli, 1999) and harbours, which together with e.g. power generators and firefighting activities/equipment are likely to be relevant sources of contamination at these sites.

2.7 KNOWLEDGE GAPS

- While legacy POPs have been monitored quite extensively both on land and in adjacent waters and sediments in Svalbard, information is scarce regarding the emerging pollutants. Concentrations of various forms of flame retardants and additives need to be measured at all settlements.
- There is limited data on composition and concentrations of CECs and microplastics in various environments and sewage in Longyearbyen. To the best of our knowledge these data are completely absent for Ny-Ålesund, Svea and Barentsburg.
- The environmental impact of the airport in Longyearbyen is being investigated, and sources and fate of contaminants related to airport and firefighting activities are being monitored in Svalbard in general. To the best of our knowledge no such assessment has been performed at the airports in Ny-Ålesund and Svea.
- Risk assessments have partly been conducted for contaminated sites, e.g. in Pyramiden, Barentsburg, Colesbukta and Ny-Ålesund, it is, however, still unclear to what extent recommendations have been followed through.
- There are a number of sites outside the settlements where soil contamination may be present but still is poorly documented, understood or remediated. These sites include Signehamna/Signedalen in Krossfjorden and 20 sites where petroleum exploration has occurred. Since documentation of these sites is vastly lacking, environmental risk assessments are partly inconclusive. New measurements of contaminant concentrations in various environmental matrixes from these sites are recommended to accommodate possible remediation actions.
- Ground and air temperatures are predicted to increase in the wake of climate change, thus compromising the barrier-like effect of the permafrost. Most dumpsites in Svalbard rest directly on the ground and may thus begin to leak contaminants, which are currently stored frozen within them, through the melted ground. These processes are poorly understood and potential hazards are poorly documented.

3 REMEDIATION OF CONTAMINATED SITES

3.1 GUIDANCE DOCUMENTS & NORWEGIAN RISK ASSESSMENT PRACTICE

The Norwegian government has developed guidance documents and contamination criteria with condition classifications for contaminated soil and sediments. These documents include:

- Guidelines on risk assessment of contaminated sites, 99:01a (Vik et al, 1999).
- Classification of condition for contaminated sites, TA-2553/2009 (Hansen & Danielsberg, 2009).
- Guidelines for risk assessment of contaminated sediments, TA-2230/2007 (Bakke et al, 2007a).
- Guidelines on classification of environmental quality in fjords and coastal waters – A revision of the classification of water and sediments with respect to metals and organic contaminants, TA-2229/2007 (Bakke et al, 2007b).

The classifications and guidelines are all primarily developed for temperate Norwegian conditions and may thus not be suitable for or applicable to Arctic conditions such as those in Svalbard.

Ecosystem structure, trophic state, temperature, permafrost, permanent ice and snow cover, extreme seasonal melting periods, remoteness, lack of infrastructure and metal, coal or petroleum bearing bedrock will affect site classification and remediation procedures (Poland et al, 2003).

Skjerstad and Gabrielsen (1998) suggested Norwegian guidelines for PCB contaminated soil on Jan Mayen. The criteria were based on established Canadian guidelines for Arctic PCB contamination (INAC, 2005) and were developed in conjunction with the risk assessment and remediation action of a contaminated dumpsite on Jan Mayen (see section 3.3.2). The Norwegian guidelines for environmental classification of marine sediments were recently reviewed with respect to metal and polycyclic aromatic hydrocarbon (PAH) contamination in Svalbard (Jensen & Evenset, 2015). This was done since Arctic ecosystems may be either more or less sensitive to contamination relative to temperate ecosystems, depending on naturally occurring background contamination. Coal bearing bedrock, e.g. leads to “naturally” high PAH levels in certain areas in Svalbard, and PAHs associated with coal is potentially less bioavailable than those associated with, e.g. an oil spill. Condition classifications may thus overestimate the risk. To our knowledge this is the only attempt as of yet to adjust criteria and guidelines to Arctic conditions in Norway. Risk assessment procedures including the use of condition classifications are described in detail in the national guidance documents and will thus only briefly be reviewed here.

3.1.1 Risk assessment

Site and situation analysis

According to the “Guidelines on risk assessment of contaminated sites, 99:01a” (Vik et al, 1999), the first step in the risk assessment procedure is to provide a detailed description of the site and analysis of the situation. This is done in order to determine whether contamination may be present or not. In this process, national “environmental targets” (Norwegian Ministry of the Environment, 2012) and local environmental goals need to be identified in order to determine the level of acceptable contamination. The following issues need to be covered:

- Type, location and extent of possible contamination sources, including known properties of suspected contaminants.
- Characterization of potential emission routes (soil, air, water).

- Evaluation of potential exposure through use of the area and characterization of recipients.
- Identification of potential user conflicts and environmental targets.

Svalbard is further covered by the Svalbard Environmental Protection Act (The Government of Norway, 2001). The Act covers the entire land area of Svalbard and its waters out to the territorial limit. The Act states:

“The purpose of this Act is to preserve a virtually untouched environment in Svalbard with respect to continuous areas of wilderness, landscape, flora, fauna and cultural heritage.

Within this framework, the Act allows for environmentally sound settlement, research and commercial activities.”

Under section 7 the Act also proclaims the use of the “precautionary principle” thus prioritizing environmental protection over other interests.

“When an administrative body lacks adequate information on the effects that an undertaking may have on the natural environment or cultural heritage, its authority under this Act shall be exercised in a manner designed to avoid possible damage to the environment.”

It is important to recognize that the law does not include contaminants originating from household or similar waste present at trace levels.

Stepwise procedure

The “Guidelines on risk assessment of contaminated sites, 99:01a” (Vik et al, 1999) outlines three steps or levels in the risk assessment procedure; 1) simplified risk assessment, 2) extended risk assessment (estimated exposure), and 3) extended risk assessment (measured exposure). What distinguishes the steps from each other is the requirement of supporting information or data and the level of uncertainty thus warranting different degrees of safety margins (Fig. 9). The point is to, regardless of available data, secure the same level of safety and protection for humans and the environment. Costs are distributed on different posts and undoubtedly more information and knowledge will be gained from level 3 than level 1 or 2 assessments.

Level 1 - Simplified risk assessment. Measured or available data on soil contaminant concentrations are compared with classification criteria for contaminated soil (Hansen & Danielsberg, 2009). The criteria consider all exposure routes despite relevance to the site in question. If concentrations are below levels of concern the risk assessment is closed, if they are above, the risk assessment can proceed to level 2.

Level 2 - Extended risk assessment (estimated exposure). Exposure routes are identified and worst case scenarios are determined. This involves source, emission, and exposure analysis where episodic events related to seasons (e.g. heavy rainfall, snowmelt) must be included. Acute and chronic exposures are compared to levels of concern and acceptance criteria. Environmental concentrations are also compared to environmental targets. If levels and exposure are exceeded remediation actions must be implemented.

Level 3 - Extended risk assessment (measured exposure). The difference between level 2 and level 3 assessments is that concentrations are actually measured instead of estimated.

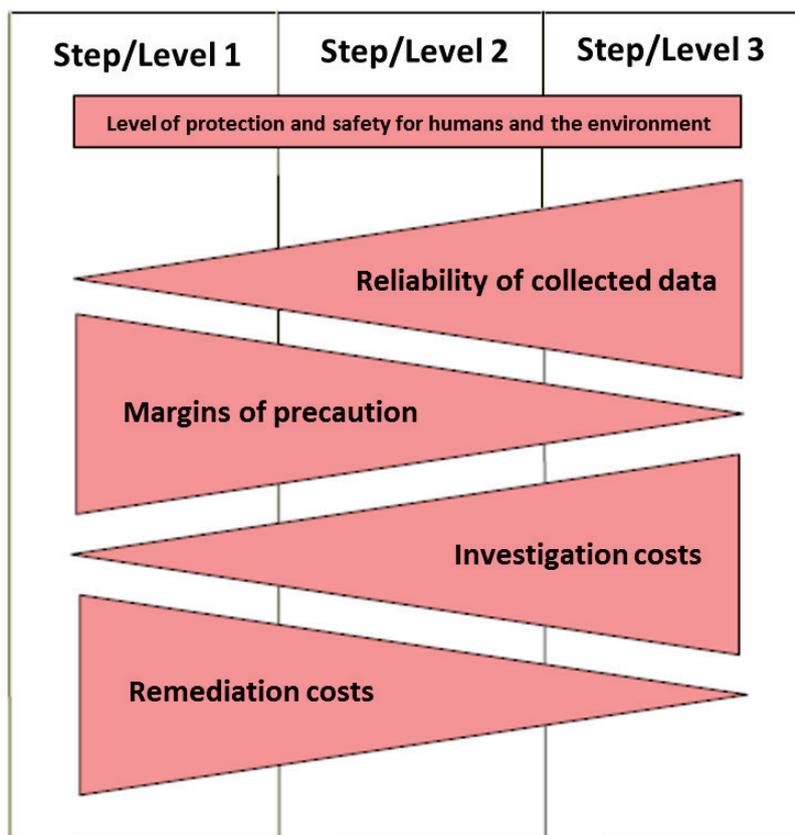


Figure 9. A stepwise structure of the risk assessment procedure aims to enable similar levels of protection for humans and the environment without equal levels of available information or data. Redrawn after Vik et al (1999).

3.2 AVAILABLE REMEDIATION TECHNIQUES

Techniques for remediation of contaminated soils are extensively reviewed and discussed in Khan et al. (2004) and are here only presented in brief with additional Arctic and Antarctic examples.

3.2.1 Excavation and *ex situ* remediation

The most obvious method for soil remediation is to excavate the area and treat the soil to remove, destroy or immobilize the contaminants. *Soil washing* involves washing excavated soil with water, solvents, detergents or surfactants, which allows treatment of complex contamination mixtures and permits the recovery of, e.g. metals for recycling and reuse. *Thermal desorption* involves heating up the soil to release and capture organic contaminants such as petroleum hydrocarbons for further use. *Bioslurry systems* are set up to enhance microbial degradation of organic contaminants and may include addition of additional substrates or microbial strains in a *bioreactor*. Contaminated soil can also be stabilized or solidified. *Asphalt batching* mixes contaminated soil into asphalt mixtures, which can be used for paving. Heating destroys many organic contaminants while the remaining contaminants become immobilized in the asphalt matrix. *Vitrification* or molten glass formation involves heating contaminated soils to extreme temperatures (1600-2000 °C). Most organic

contaminants are destroyed while metals and radioisotopes become incorporated in the resulting leach-resistant and inert glass product.

3.2.2 In situ remediation

It is environmentally and economically desirable to enable removal of contaminants from soil without having to excavate and transport soil from the area. Physiochemical, and biological techniques, alone or in combination, have thus been developed to remediate contaminated sediments *in situ*. Physiochemical techniques include *aeration*, *soil flushing*, *soil vapour extraction (SVE)* and *sorbent amendment*, while biological techniques include *bioventing*, *landfarming*, *biopiling* and *phytoremediation*.

Physiochemical techniques

Aeration is mainly used to get rid of SVOCs, pesticides and fuels and is accomplished by spreading contaminated soil over a larger surface area and intermittently turning it to stimulate evaporation. *Soil flushing* means flooding contaminated soil *in situ* with an extraction medium (*e.g.* EDTA for metals). The flooding liquid which will contain the contaminants is then pumped up and collected for further remediation. *Soil vapour extraction (SVE)*, soil venting or vacuum extraction involves installing under-pressure wells in several places of a piece of land, *e.g.* impacted by volatile or semi-volatile organic contamination (VOC/SVOC) (Fig. 10). Extracted vapours are then passed through activated carbon filters prior to being released into the surrounding air (Halmemies et al, 2003). *Sorbent/complexing agent amendment* involves the addition of, *e.g.* activated carbon or EDTA to absorb the freely dissolved (bioavailable) fraction of organic contaminants and metals respectively (Brändli et al, 2008; Khan et al, 2004). Addition of activated carbon to other sorbents has been successfully performed leading to reduced PCB and DDT bioavailability in intertidal and marine sediments as well (Cornelissen et al, 2011; Schaanning et al, 2006).

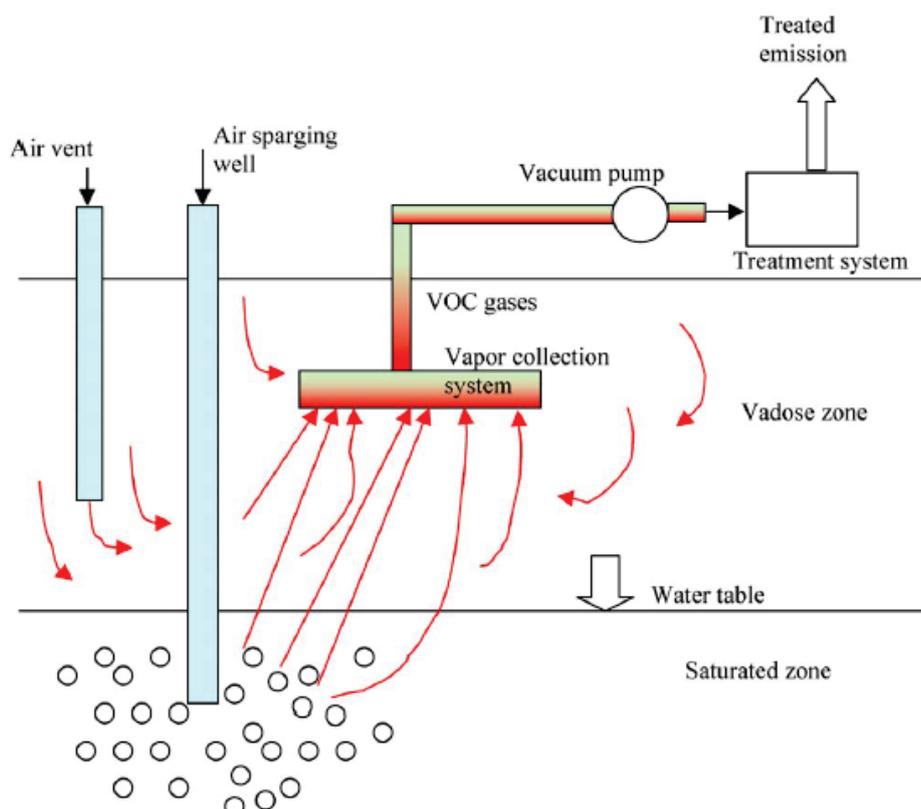


Figure 10: Soil vapour extraction for *in situ* remediation of contaminated soil (Khan et al, 2004).

Biological techniques

Bioventing involves injecting air into soil to promote aerobic microbial degradation of organic contaminants. It also facilitates degassing of VOCs into the atmosphere. *Landfarming* involves spreading often petroleum contaminated soil in a thin layer (<1.5 m) and stimulate aerobic microbial degradation through aeration and addition of supplementary nutrients. Successful bioremediation of both diesel hydrocarbons and trimethylbenzene contaminated soil has been performed at Resolution Island, Canada (Paudyn et al, 2008) and in Barrow, Alaska (McCarthy et al, 2004). *Biopiling* only differs from landfarming in that contaminated soil is piled in heaps. Biopiling has successfully removed up to 90% of hydrocarbons from diesel fuel contaminated tundra soil during the course of one year *in situ* (Mohn et al, 2001). Biopiling has also been used to remediate diesel contaminated soil in several places in Antarctica (ATCMXXXVIII-CEP6, 2015d). *Phytoremediation* uses plants to remove or stabilize soil-associated contaminants. The five types of phytoremediation include 1) rhizofiltration, where contaminants are taken up by plant roots; 2) phytoextraction, where the whole plant accumulates contaminants from the soil; 3) phytotransformation, where contaminants are degraded through plant metabolism; 4) phytostimulation or plant-assisted bioremediation, where microbial degradation is stimulated through the activities of plants in the root zone; and 5) phytostabilization, which uses plants to reduce the migration of contaminants through the soil medium (Barter, 1999).

3.2.3 Encapsulation

Encapsulation is a form of storage where the contaminated soil is physically isolated from the surrounding environment by means of barriers. Barriers can be built constructions or capping or enclosing masses of soil or gravel.

3.3 SOIL REMEDIATION IN POLAR REGIONS - CASE STUDIES

The polar regions present unique challenges, which make remedial choices obvious in temperate or tropical regions difficult or even impossible to implement. Clean-up of contaminated sites in the developed world has received extensive resources in the past 30 years while investigations and research concerning Arctic and Antarctic contaminated site remediation are scarce (Poland et al, 2003). There are knowledge gaps when it comes to development of Arctic risk assessment models and the information required performing them such as, fate and effects of contaminants in Arctic ecosystems and migration rates of contaminants through permafrost. Poland et al (2003) state that knowledge is only starting to be gained regarding challenging issues such as landfill construction, contaminant-barrier design, cold climate bioremediation, and transfer of technologies such as solvent extraction and thermal desorption. The situation is similar for Antarctica with the exception that soil contamination often originates from operations associated with research stations and not industrial activities (Poland et al, 2003).

Aside from the mentioned knowledge gaps, the polar regions present challenges related to remoteness, logistics, climate, health and safety. The remoteness and an often extensive area subject to remediation make operations immense and costly. The remoteness implies transportation of all equipment required for the construction work, maintenance and living. Transportation becomes hazardous due to bad and highly variable weather conditions, pack ice or icebergs. The field season is short, often restricted to two months during the year. Important safety issues on site are fires, which may be difficult to extinguish when larger water supplies are frozen, frost bites from working in cold environments, polar bears (Arctic) and exposure to the contaminants from the site itself. There are currently no readily available solutions for contaminated site remediation in the Arctic. Each situation presents its own problems and possibilities and a combination of approaches and techniques is often used. There are, however, attempts and successful examples to learn from. Below follows a selection of examples illustrating obstacles and solutions from Arctic remediation projects already carried out.

3.3.1 The DEW Line

One of the largest remediation projects carried out in the Arctic involves the clean-up of DEW (Distant Early Warning)-line sites in the Canadian Arctic. The DEW Line was part of the cold war radar and communication defence system established during the early 1950s (Fig. 11) (Fletcher, 1990). In 1985 Canada and U.S.A. agreed to replace the radar stations with a satellite based system. A series of risk assessments were thus carried out for all 42 Canadian DEW Line stations (63 in total) between 1989 and 1993 within the framework of the Dew Line Clean Up Project (DLCU) run by the Department of National Defence and the Department of Indian and Northern Affairs (Analytical Services Unit, 1995; Analytical

Services Unit (ASU), 1997; Analytical Services Unit (ASU), 1999; Analytical Services Unit (ASU), 2000; ESG, 1991; ESG, 1993a; ESG, 1993b; ESG, 1993c; ESG, 1994a; ESG, 1994b; ESG, 1995a; ESG, 1995b). The DLCU identified contaminants of concern and developed a protocol including a set of risk-based criteria for clean-up (INAC, 2005). Methodologies were prepared, but solutions were developed and refined during the multiyear efforts required at each site (Poland et al, 2001). Thirty two of the 42 DEW Line stations were situated in the Nunavut province, Canada.

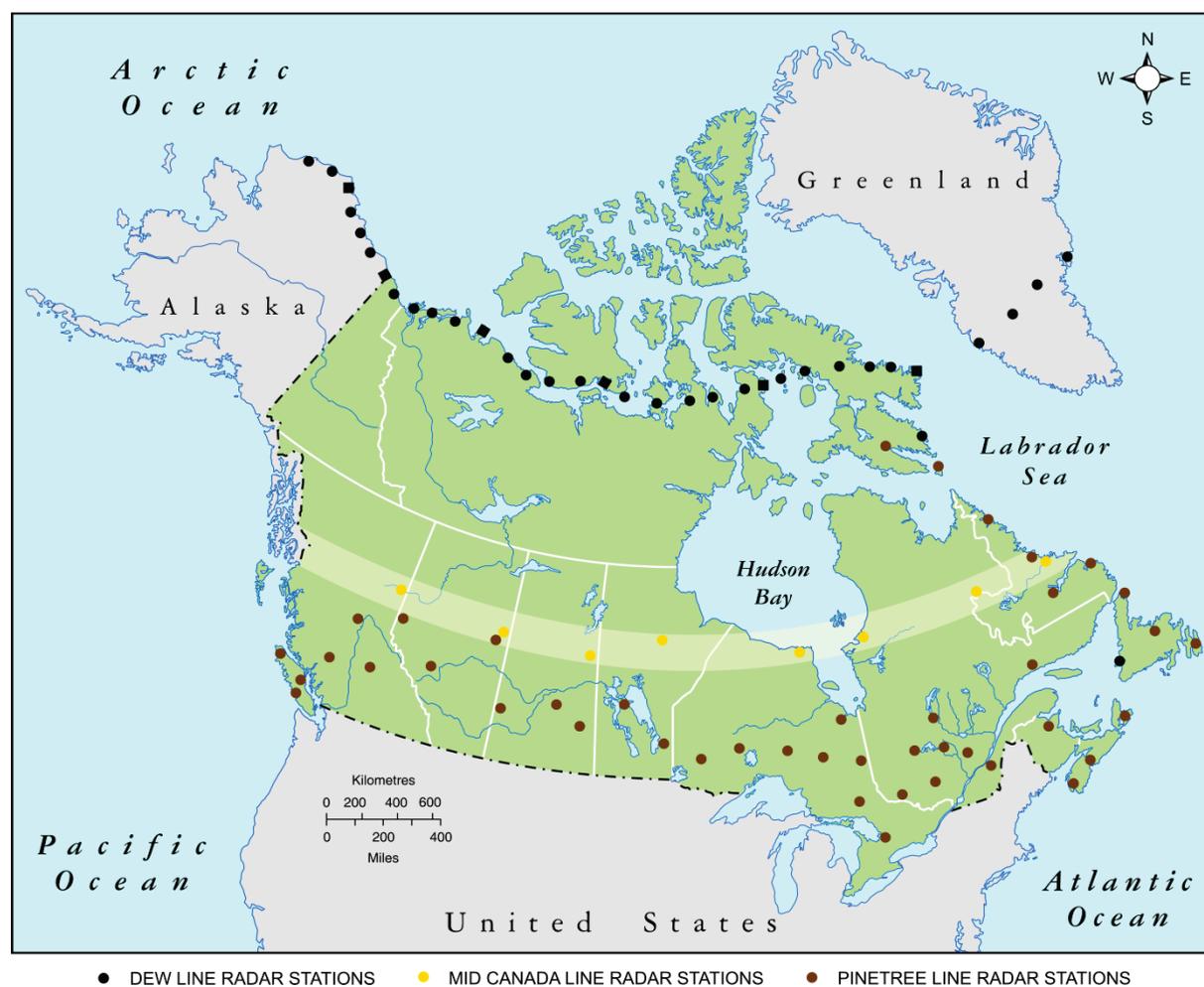


Figure 11. North American radar defence systems established during the cold war. Map courtesy of the Canadian Military Journal/Vol 8 No 2/Christopher Johnson.

BAF-5, Resolution Island, Nunavut

Resolution Island is located at the south eastern tip of Baffin Island, Nunavut. The main DEW Line station (BAF-5) at this site resides on a summit 360 m above sea level overlooking Brewer Bay. In the summer, the area exposes bare bedrock with occasional pockets of soil. Polar bears frequent the site between June and September, and seals and whales often visit Brewer Bay. When operative (1953-1972), the base consisted of 40 permanent buildings and accommodating at most 200 military personnel. When vacated in 1972, hazardous materials such as PCBs, mercury and petroleum products were left along with barrels, debris, eight

dumpsites and abandoned buildings. Over 8000 kg of pure PCB (Arochlor 1260) was left at the site associated with various matrices and was the main focus of the remedial actions. Most of the PCBs originated from specific buildings, with leakage along a valley and towards a beach before entering the sea at Brewer Bay (Fig. 12). PCBs were also found in house paint and scattered electrical equipment. Another important PCB source was a dumpsite, harbouring transformers and other electrical devices, with drainage pathways into Brewer Bay. Pack ice and icebergs make approaches from sea hazardous, while fog and treacherous weather conditions make landing on the very short air strip hazardous. In the winter, eight metres high snow drifts block roads. A new camp was established in 1993 to accommodate environmental investigations and remediation operations, which were completed in 2006. A combined set of approaches was applied to solve the numerous different contamination problems at the site (Kalinovich et al, 2008; Kalinovich et al, 2012; Poland et al, 2001).

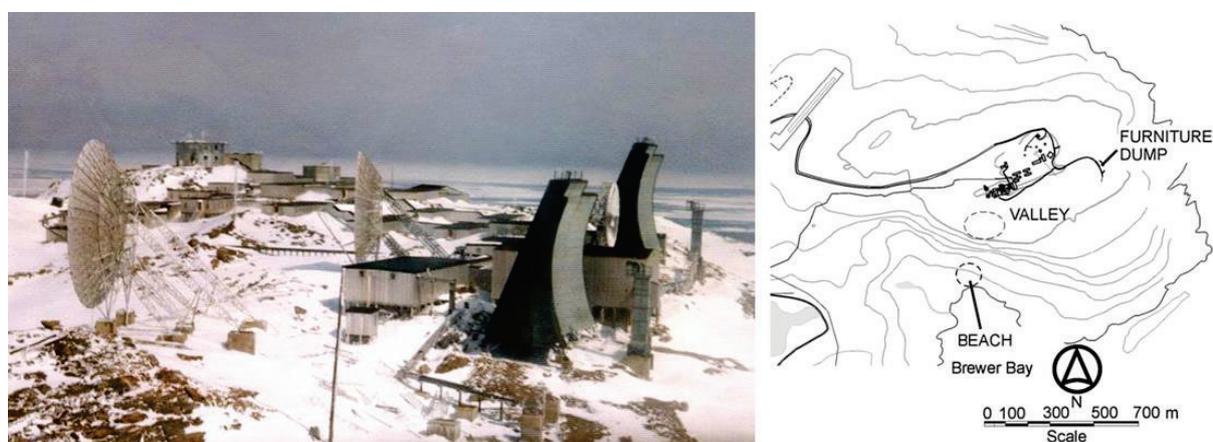


Figure 12. Resolution Island, Nunavut, Canada. Photo courtesy Rob Hopkins. Map of site and drainage barrier sites (Kalinovich et al, 2012).

Contaminated material

After a series of risk assessments (Analytical Services Unit, 1995; Analytical Services Unit (ASU), 1997; Analytical Services Unit (ASU), 1999; Analytical Services Unit (ASU), 2000; ESG, 1994a; ESG, 1995b), the first task was to secure all PCB sources. Transformer oils were transferred into safe containers and PCB-containing material and electronic devices were collected and packed safely. This included electronic devices and PCB-contaminated material from the dumpsite. Collected contaminated material was shipped out for destruction in southern Canada. This action removed half of the PCBs present, leaving 4000 kg of PCB distributed in over 20000 m³ soil.

Contaminated soil

Three areas were identified containing potentially high concentrations of PCBs. A grid system (20 × 20 m) was constructed covering the presumed contaminated areas. Soil samples were collected according to the grid and analysed for PCBs at an on-site lab in order to define a contamination map. Soils were then classified according to the DLCU protocol and assigned appropriate remediation action (INAC, 2005). Soils containing > 50 µg g⁻¹ PCBs (CEPA soils) were excavated, and the area vacuumed, where after the soil was retained and sent for

destruction in southern Canada. Each grid square was excavated individually down to the bedrock or to the permafrost layer. Ninety-six percent of the PCB-contamination was removed from the BAF-5 site after recovering contaminated material and contaminated CEPA soil (Kalinovich et al, 2008). Soils containing 5-50 $\mu\text{g g}^{-1}$ PCBs (Tier II) and 1-5 $\mu\text{g g}^{-1}$ PCBs (Tier I) were then excavated. Tier II soils needed either to be shipped off or stored on site isolated from the Arctic ecosystem, while Tier I soils only required burial into a non-hazardous landfill. An engineered, lined landfill was created to contain the Tier II soil while Tier I soils were disposed of at another landfill site. Both were covered with uncontaminated soil. Various destruction options were discussed for the CEPA soil also including on-site remediation. Shipment to a certified destruction plant provided the least expensive solution.

Drainage barriers

Due to leakage of PCBs from contaminated soil into the sea, three drainage barriers were designed and installed in the leachate pathways at the valley, beach and furniture dumpsites (Fig. 12). The funnel-like drainage barriers with filters were designed to retain PCB-contaminated particles transported with surface water runoff (Fig. 13). The presence of petroleum products along one of the drainage pathways led to increased transport of PCBs due to their higher solubility in these solvents as compared to water. The drainage barriers were monitored annually after installation, appearing to be highly functional with successful retention of remaining PCB-contaminated particles.

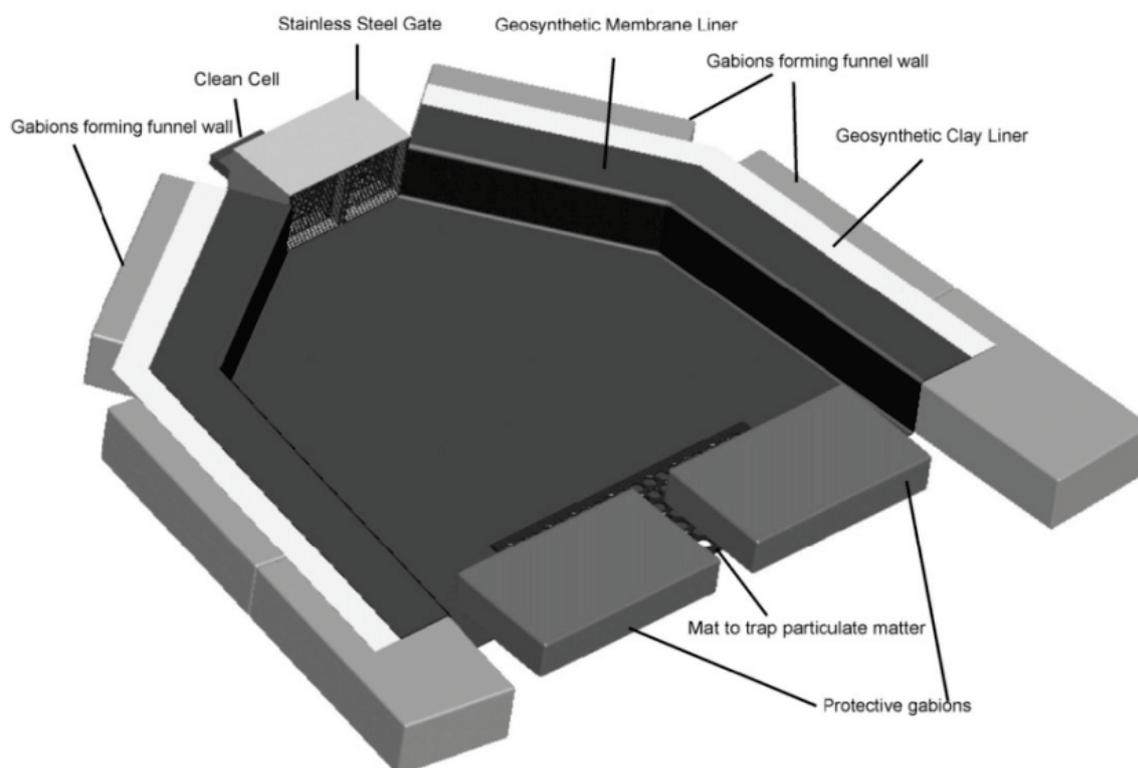


Figure 13. Prototype illustration of drainage barrier at BAF-5, stainless steel gate box dimensions 1,5×0,5 m (Kalinovich et al, 2008).

3.3.2 The Jan Mayen dumpsite

Jan Mayen is situated 550 km north-east of Iceland and 500 km east of Greenland, and belongs to Norway. The northernmost active volcano Beerenberg is situated on the island. Jan Mayen hosts a unique wildlife with large colonies of migrating seabirds and typical Arctic marine waters dominated by polar cod (*Boreogadus saida*) and capelin (*Mallotus villosus*) (Gabrielsen et al, 1997b). Large parts of the year the island is surrounded by sea ice. The majority of Jan Mayen and its coastal waters became a natural reserve 19 November 2010, while the environmental management plan was only recently established (Fylkesmannen i Nordland, 2016). The island has traditionally been used for whaling and hunting, but in 1922 the Norwegian Meteorological Institute established a measuring station at Jan Mayen, which was later complemented by military radio and satellite stations.



Figure 14. Jan Mayen, Norway with the Trollsletta dumpsite, <http://topojanmayen.npolar.no/>.

In 1993 and 1994 high THC ($13.400 \mu\text{g g}^{-1} \text{DW}$) and PCB ($0.2 \mu\text{g g}^{-1} \text{DW}$) concentrations were detected at the military radar station dumpsite at the settlement Olonkinbyen (Fig. 14). The PCBs originated from transformer oil, which had been deposited at the now closed dumpsite at Trollsletta. The dumpsite is located on a slope, 2-5 m from the sea shore.

Environmental investigations which focused on PCB contamination established that dumpsite soil PCB concentrations ranged between 0,06 and 35,8 $\mu\text{g g}^{-1}$ DW (average 3 $\mu\text{g g}^{-1}$ DW) while samples collected ~20 m from the dumpsite had contained between 0,002 and 0,06 $\mu\text{g PCB g}^{-1}$ DW (Gabrielsen et al, 1997a). Samples were also collected from various seabird species. Congener patterns differed between different bird species and concentrations increased with increasing trophic position (Gabrielsen et al, 1997a). Body burdens of PCBs in kittiwake (*Rissa tridactyla*) and glaucous gull (*Larus hyperboreus*) corresponded with levels found at other Arctic Norwegian locations, indicating background contamination, thus excluding the dumpsite as a potential PCB source to seabirds. Arctic char (*Salvelinus alpinus*) was sampled from the freshwater lagoon on the island (Fig. 13), showing high concentrations of PCBs. The PCB fingerprint did however not correspond with that of the dumpsite and the source connection with the dumpsite was again rejected. Marine fish were sampled along a transect perpendicular to the Trollsetta shore, only showing elevated PCB concentrations in sole (*Hippoglossides platessoides*).

After additional geological investigations, the risk assessment established that the dumpsite land masses should not be moved, but instead be covered with uncontaminated soil to avoid wind-driven contaminated particle transport to surrounding land and waters (Gabrielsen et al, 1997a). This decision was based on the low average PCB concentrations (3 $\mu\text{g g}^{-1}$ DW) measured in soil corresponding to Tier I soils (1-5 $\mu\text{g g}^{-1}$ DW) according to the Canadian DLCU protocol (INAC, 2005). This protocol was used since guidelines for contaminated soil were lacking for the Norwegian Arctic. According to the Canadian protocol Tier I soils are to be deposited in a non-hazardous landfill and covered with clean landfill. In the wake of these investigations guidelines for PCB-contaminated soil were established for Jan Mayen (Skjeggstad & Gabrielsen, 1998). Similar guidelines are still lacking for Svalbard. The Norwegian Armed Forces Administration is responsible for the continued monitoring of the Jan Mayen dumpsite with particular focus on the erosion of the landfill into marine waters.

3.3.3 Landfarming in Alaska and Nunavut

The most desirable form of remediation involves degradation or mineralization (conversion into CO_2) of soil-associated contaminants on-site. BTEX, PAHs and other hydrocarbons have been successfully removed from contaminated soil on a field scale in the Arctic using landfarming (McCarthy et al, 2004; Paudyn et al, 2008; Sanscartier et al, 2009). The method typically involves the addition of nutrients and water, and periodic tilling to mix and aerate the soil. The aim is to stimulate natural biodegradation performed by existing microbial communities. Microbes capable of biodegrading many types of organic contaminants are found even in the harshest of environments (e.g. Arhelger et al, 1977; Atlas & Bartha, 1992; Atlas & Schofield, 1975; Cerniglia, 1992; Gerginova et al, 2013; Valentin et al, 2006). Additional amendments include e.g. bulking agents to increase aeration, co-substrates to stimulate microbial metabolism, lime to adjust pH and inoculation with biodegrading bacteria. Landfarming is an attractive remediation alternative for remote sites because it is technically simple and relatively inexpensive (McCarthy et al, 2004). Landfarming is typically performed during the two warmest months of the year.

Barrow, Alaska

In 1988 a land exchange was signed between the US Government and the local native administration (Ukpeangvik Iñupiat Corporation) in Barrow, Alaska. The now closed Naval Arctic Research Laboratory just north of Barrow had been situated on the exchanged land since the 1940s, and large areas were contaminated by diesel oil around fuel storage sites. A risk assessment was performed in 1997 revealing that approximately 7000 m³ soil was contaminated with petroleum hydrocarbons, with diesel range aliphatic concentrations up to 25000 mg kg⁻¹ thus exceeding the Alaska Department of Environmental Conservation (ADEC) clean-up levels. The most contaminated soil was excavated and treated *ex situ*. Landfarming was chosen for remediation of the moderately petroleum-contaminated soil, supported by previous experimental studies at the site (Braddock et al, 1999).

During the beginning of the summer thaw (first week of July) in 2003, 2800 m³ clean soil was removed from a large plot (0.6 m depth), and replaced with 2900 m³ moderately contaminated soil, supported around all edges with additional clean soil. The plot was thus elevated compared to the surrounding ground. Two commercially available fertilizers (monoammonium phosphate and urea) were added to a P:N ratio of 2:1. Addition was designed not to exceed 100 mg N and 50 mg P kg⁻¹ soil respectively. Exceeding these concentrations did not stimulate biodegradation rates further (Braddock et al, 1999). Fertilizer was added twice, and the soil was exposed to regular tilling 10 hours a day 6 days a week. The soil was completely mixed down to 1.5 m depth, i.e. just above the permafrost layer. After the 55 days of intense remediation activity the BTEX and all petroleum hydrocarbons were either absent or well below the ADEC allowable soil concentrations. The average monthly temperatures during the landfarming months June, July and August were 1.3, 4.9 and 2.1 °C respectively. This bioremediation activity demonstrates landfarming as a successful and cost-efficient option for petroleum-contaminated soil remediation under extremely harsh Arctic conditions.

DEW Line, Resolution Island, Nunavut

A successful trial followed by large-scale landfarming of contaminated soil was performed at the BAF-5 site on Resolution Island, previously described. At this multi-contaminated site, soil heavily contaminated with diesel fuel was used to explore the possibility for *in situ* bioremediation. Contaminated soil was placed in plots on top of levelled clean soil. Plots were exposed to either of four treatments, 1) no amendment, 2) daily tilling, 3) tilling every fourth day, or 4) fertilizer added and tilling every fourth day, continuing all through the summer months. After three years of continued maintenance of the plots during the summer months, 80% of the petroleum hydrocarbons were removed in the fertilized and tilled plots. Successful, large-scale landfarming was then performed, based on the most successful experimental design, to remediate diesel-contaminated soils at the BAF-5 site (Paudyn et al, 2008).

3.3.4 Contaminated soil remediation in Antarctica

Antarctica is considered the most pristine place on earth (Poland et al, 2003). However, in this fragile environment increasing levels of pollutants follow in the wake of growing tourist and fisheries activities as well as a result of scientific operations and their related logistic support (Fig. 15). Soils and coastal sediments are significantly polluted near scientific stations particularly by PAHs (Curtosi et al, 2007). Snape et al (2001) estimated that the volume of unconfined tip materials and the volume of petroleum-contaminated soil in Antarctica may each be greater than 1 million m³. Most importantly, this contamination is located in the rare ice-free areas, which also serve as main habitats for wildlife (CEP, 2014).



Figure 15. Major permanent research stations in Antarctica. Illustration by Hugo Ahlenius, UNEP/GRID-Arendal, http://www.grida.no/graphicslib/detail/major-research-stations-in-Antarctica_1316

In contrast to the Arctic, Antarctica has no historical or present permanent communities, no military bases, no mining or other industrial activities, and the proximity to land masses and polluting industrial communities is vast (Poland et al, 2003). In recognition of the uniqueness of the Antarctic environment, the Antarctic Treaty Parties adopted “Recommendation VIII-11” already in 1975, which was the first step towards an agreed guidance manual for the appropriate management and disposal of waste generated by expeditions and stations, with a view to minimize impacts on the Antarctic environment. This recommendation is a living

document with its latest additions compiled in “The Antarctic Clean-up Manual Resolution 2 (2013) (updated 2014)” (CEP, 2014). This document also provides guidance for remediation actions, and is progressive in that it promotes the use of e.g. *in situ* techniques instead of excavation and shipping when remediating petroleum-contaminated soil. In bright contrast, Arctic environmental issues are regulated by each country individually, which significantly complicates coordinated efforts for environmental protection and clean-up (Poland et al, 2003).

In situ remediation at the Brazilian Research Station on King George Island

In 2012 approximately 70%, including the main building, of the Brazilian Antarctic Research Station "Estação Antártica Comandante Ferraz – EACF" located in Admiralty Bay, King George Island, was destroyed in an accidental fire. The fire broke out in the machine room housing the power generators. Investigations succeeding the accident identified hydrocarbon contamination in approximately 700 m³ of soil caused by diesel spills, particularly in the area where the electricity generators and the diesel tanks were located. To minimize environmental impact, an emergency remediation action was initiated aimed at cleaning up the diesel-contaminated soil (ATCMXXXIX-CEP6, 2016; ATCMXXXVIII-CEP6, 2015a; ATCMXXXVIII-CEP6, 2015b).



Figure 16. The Brazilian Research Station, Antarctica. Installation of a bioventing system during *in situ* remediation of diesel-contaminated soil using “biocava” techniques (ATCMXXXIX-CEP6, 2016).

Based on recommendations in the Antarctic Clean-up Manual and studies documenting the presence of hydrocarbonoclastic microbes in natural soils from the area (Cury et al, 2011; Cury et al, 2014), augmented *in situ* remediation was chosen as a plausible and cost-effective alternative for diesel clean-up. The clean-up procedures were partly experimental including the construction of a “biocava” and a biopile. Biocava construction was initiated in January 2014 where a large area (264 m²) with contaminated soil was excavated (l: 22 m, w: 12 m, d: 2.5 m). The excavated pit was lined with a geomembrane (high density polyethylene membrane, thickness 2 mm) and supplemented with aeration pipes for bioventing (Fig. 16). The excavated soil was amended with nutrients and loaded back on top of the geomembrane and pipes and covered. Increased oxygenation and nutrient supply was expected to stimulate microbial degradation and mineralization of the soil associated diesel. Biopiling of diesel-contaminated soil excavated from another part of the impacted site was initiated in January 2015. The biopile consisted of 450 m³ of diesel-contaminated soil amended with fertilizers and covered by a geomembrane (ATCMXXXVIII-CEP6, 2015a). Soil sampling is planned to be performed in the beginning and end of each summer season at both bioremediation sites to monitor the progress of diesel biodegradation (ATCMXXXIX-CEP6, 2016).

In situ remediation at Australian Research Stations

Similar biopile based techniques have been used to remediate diesel-contaminated soil in other parts of Antarctica (ATCMXXXVIII-CEP6, 2015c; ATCMXXXVIII-CEP6, 2015d). In 2010 three 200 l drums of fuel were transported by helicopter from Davis station (Australian Antarctic Division) to a nearby skiway (ATCMXXXVIII-CEP6, 2015c). At a height of 60 m the load became unstable and the drums had to be cut loose. On impact the drums ruptured and spilled diesel fuel contaminated a large area of sandy soil close to Lake Dingle. The Antarctic Clean-Up Manual was followed to aid decision making regarding remediation actions. The contaminated soil was recovered during two expeditions by excavation and vacuum cleaning and transported to Davis station for biopiling. These expeditions were performed jointly by Australian, Chinese and Russian Antarctic programmes. After a period of three years the diesel contamination levels of the biopiled soil had reached levels allowable for use in building footings. Aside from other advantages associated with *in situ* remediation, being able to keep the soil on the continent is preferred since soil is a limited and valuable resource in Antarctica.

In 2005 a remediation project was initiated following an oil spill at Casey Station (Australian Antarctic Division) in 1999 (ATCMXXXVIII-CEP6, 2015d). Before any remediation took place, investigations on natural biodegradation and evaporating rates were performed at the spill site concluding that the spill was almost unchanged even after five years in the Antarctic soil (Snape et al, 2006; Snape et al, 2005). Because the amount of contaminated soil was extensive and also located on a slope risking to leak contaminants into the sea, both biopiles and a permeable reactive barrier (PRB) filtering system were constructed (Fig. 17). Biopiles were amended with nutrients and aerated using a piping system. The piping system also functioned as a vapor extraction system for VOCs by applying vacuum to one side and drawing fresh air through the biopile, then leading the vapor filled air out through an activated carbon filter. After four years of operation the soil contained only one fifth of the original

diesel concentration. All biopiling projects document a slow, but steady reduction in petroleum hydrocarbon concentrations thus reporting them as promising remediation techniques for hydrocarbon-contaminated soils in cold remote environments.

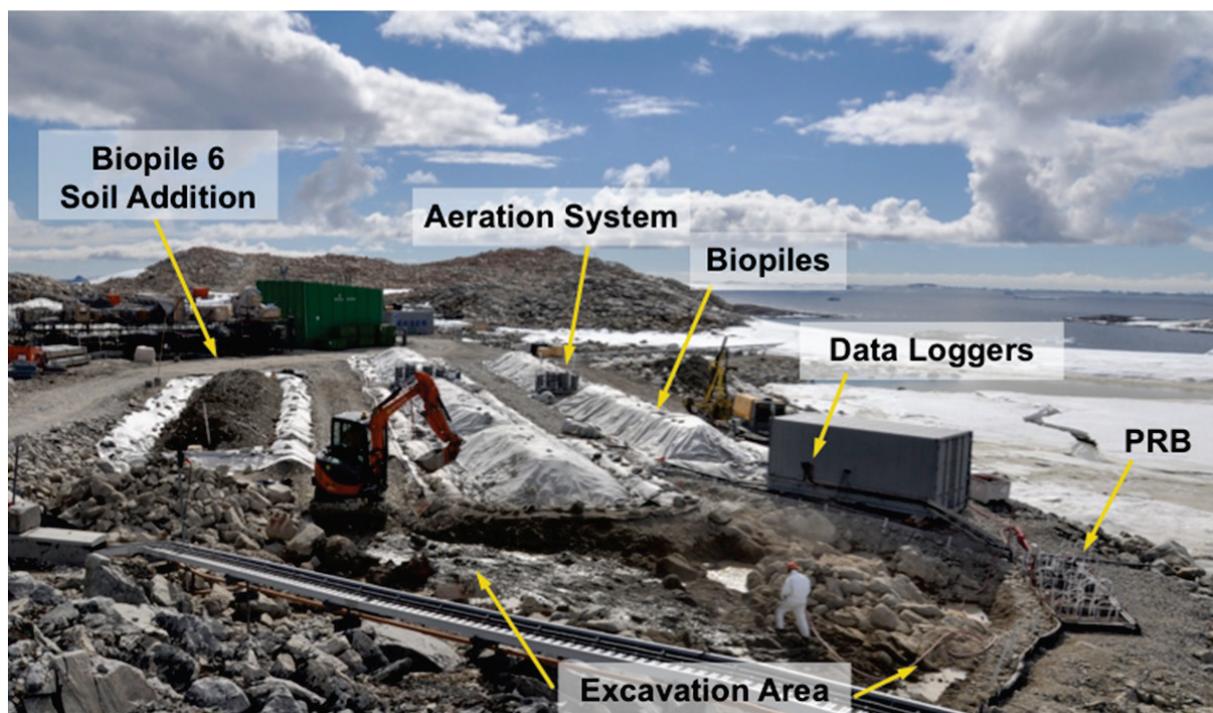


Figure 17. Remediation of fuel-contaminated soil using biopile and PRB (permeable reactive barrier) technology at Casey Station (Australian Antarctic Division). Construction site showing key features (ATCMXXXVIII-CEP6, 2015d).

3.4 DISCUSSION AND RECOMMENDATION

The most important conclusion from this review of reports and peer reviewed literature is that remediation solutions are site specific, and that the techniques available for remediation actions primarily depend on the type of contamination present. For highly persistent contaminants such as PCBs and metals, options are fewer than for contaminants that are actually degradable. It is well worth exploring *in situ* remediation/bioremediation options, e.g. in cases of petroleum pollution. Petroleum-polluted sites are found both within and outside the main settlements in Svalbard (e.g. at the 20 petroleum exploration sites), and here *in situ* bioremediation likely offers a viable remediation solution. Several successful bioremediation projects have been carried out under Arctic and Antarctic low temperature conditions, implying both lower costs and efforts.

It is clear that there are no ready-made solutions for the remediation of contaminated sites in polar regions. Knowledge gaps are present in the background information required for risk assessments, in the risk assessment procedure itself and in the relative efficiencies of various remediation options (e.g. Poland et al, 2001). Remediation projects will be exploratory and experimental and may require additional cross-disciplinary research before being initiated or completed, thus demanding sufficient time and financial support. Some of the remediation

case studies presented here lasted for 10 years or longer, often in the form of combined research and practical remediation projects. The most extensive remediation operation carried out in the Arctic terrestrial environment is the restoration of the multi-polluted and severely PCB-contaminated, abandoned military sites in the Canadian Arctic along the DEW Line. Investigations, risk assessments and remediation actions have been continuously proceeding there since 1985, and some areas are still being monitored. The estimated cost for the DLCU project until now is ~580 million CAD (CRS, 2008). When initiating remediation projects in the Arctic it is advisable to consult existing expertise, information and knowledge gained from already conducted contaminated site remediation projects, such as the DEW Line project or the bioremediation projects carried out in Antarctica. The present report refers to a substantial part of the literature produced both during the DLCU project and Antarctic bioremediation projects.

In Antarctica, *in situ* bioremediation using biocava and biopiling techniques has been suggested and implemented as the most effective method for remediating petroleum-contaminated soil (CEP, 2014). The techniques are particularly useful at sites where the contamination extends across larger areas, which is often the case at sites with historic pollution. Many of these projects show very promising results but are still under evaluation. In the near future these projects will provide important insight regarding the usefulness and efficiency of *in situ* bioremediation methods in polar regions. It is, however, important to recognize that while many Arctic contaminated sites are both abandoned and remote, the Antarctic polluted sites are often associated with research stations having the advantage of being inhabited for longer periods of time, at least during the summer months, thus allowing for maintenance of multi-year remediation projects without major additional logistics or costs. Historic and present pollution issues are more complex in the Arctic than in the Antarctic both from contamination and remediation perspectives.

Environmental risks associated with local pollution sources may have to be re-evaluated in times of climate change. Due to unique climatic and hydrological conditions, contaminant transport processes in Arctic soil are substantially slower than in areas with a temperate climate. Likewise, the groundwater-borne contaminant transport is comparably slow due to the small amounts of groundwater present and the limited number of warmer months. The low Svalbard temperatures contribute to slowing down free-phase transport of oil contaminants and also to increase the particle sorption of most organic contaminants, thus making contaminants less mobile and prone to enter the ecosystem (Breedveld & Skedsmo, 2000c). Biodegradation (foremost by microbes) does, however, also slow down, leading to increased “life times” of the organic contaminants in the environment. Contaminated Arctic soils thus sequester contaminants which are ready to be released and enter food chains as temperatures increase due to climate change. Climate change is also relevant in relation to Arctic dumpsites, which rest directly on the ground. The permafrost acts as a barrier preventing contaminants from entering the ground and groundwater (Løvteit, 2012). With rising temperatures this barrier is broken. In this light it is advisable not to delay any impending remediation actions in the Arctic.

Norway has a well-developed system for classification and risk assessment of contaminated ground sites developed for the temperate mainland (Hansen & Danielsberg, 2009; Vik et al, 1999). Developing a corresponding system adapted to Arctic conditions would be useful for Norway. In desolate, contaminated places like many of those in Svalbard, present risk assessment procedures will conclude that humans and sometimes ecosystems are unlikely to come in contact with the contaminants in question even though concentrations are high, thus potentially rejecting the necessity to remediate. Furthermore, traces of environmental pollutants from regular household or similar discharges are not covered by the regulations concerning environmental contaminants, debris and fees for sewage and garbage in Svalbard (The Government of Norway, 2002). The decision to remediate or take action to prevent potential future contamination in these remote contaminated sites then becomes a political question resting on the Svalbard Environmental Protection Act (The Government of Norway, 2001), economic priorities and good intentions.

Finally, while remediation concerns already contaminated sites, we do have the opportunity to assess anticipated contamination issues before they become hazards. This can be done by exercising the precautionary principle advocated in the Svalbard Environmental Protection Act (The Government of Norway, 2001). Such proactive initiatives require active choices regarding e.g. energy options, sewage treatment, transportation alternatives and discharges.

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