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Contamination, regulation, and remediation: an introduction to bioremediation of petroleum hydrocarbons in cold regions

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1.1 Introduction

Oil and fuel spills are among the most extensive and environmentally damaging pollution problems in cold regions and are recognized as potential threats to human and ecosystem health. It is generally thought that spills are more damaging in cold regions, and that ecosystem recovery is slower than in warmer climates (AMAP 1998; Det Norske Veritas 2003). Slow natural attenuation rates mean that petroleum concentrations remain high for many years, and site managers are therefore often forced to select among a range of more active remediation options, each of which involves a trade-off between cost and treatment time (Figure 1.1). The acceptable treatment timeline is usually dictated by financial circumstance, perceived risks, regulatory pressure, or transfer of land ownership.

In situations where remediation and site closure are not urgent, natural attenuation is often considered an option. However, for many cold region sites, contaminants rapidly migrate off-site (Gore *et al.* 1999; Snape *et al.* 2006a). In seasonally frozen ground, especially in wetlands, a pulse of contamination is often

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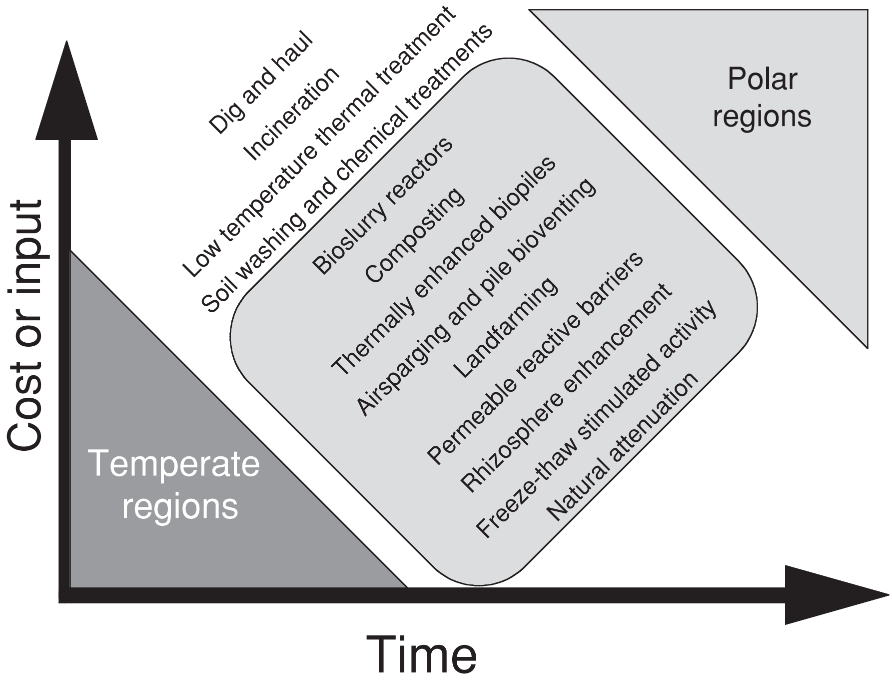

Figure 1.1. Cost-time relationship for remediation options that are suitable for petroleum contaminants. Note that cost and time for a given treatment type are invariably greater in cold regions. Boxed treatments are those considered within the scope of this book (modified after Reynolds *et al.* 1998).

released with each summer thaw (AMAP 1998; Snape *et al.* 2002). In these circumstances natural attenuation is likely not a satisfactory option. Simply excavating contaminants and removing them for off-site treatment may not be viable either, because the costs are often prohibitive and the environmental consequences of bulk extraction can equal or exceed the damage caused by the initial spill (Filler *et al.* 2006; Riser-Roberts 1998). Similarly, in-ground incineration does not effectively treat spills, but rather causes downward migration of contaminants and permafrost degradation through heating (AMAP 1998; Filler and Barnes 2003; UNEP-WCMC 1994).

In situ or on-site bioremediation techniques (Figure 1.1) offer a relatively low-cost approach for managing petroleum-contaminated soils in cold regions, with the potential to achieve reasonable environmental outcomes in a timely manner. The challenge for scientists, engineers, and environmental managers is to derive or refine a range of remedial strategies that are well suited or optimized for cold region conditions. The overall aim of this monograph is to document techniques and scientific principles that underpin good remediation practices so that managers can remediate petroleum hydrocarbons to an appropriate level as quickly and cheaply as possible. This chapter provides an overview of petroleum contamination, regulation, and remediation in cold regions. It describes some of the regulatory frameworks that govern how spills are dealt with in a variety of regions, and provides some recent case studies of how guidelines are developing or evolving, and how petroleum remediation in cold regions is currently viewed in the current regulation context. The chapter concludes by making the case for further quantitative information for development of petroleum remediation guidelines that are more appropriate to cold regions.

1.2 Review – contamination, regulation, and remediation

1.2.1 Contamination: reason for concern[1]

Many petroleum products are used, stored, transported, and subsequently spilled in the cold regions. Colin Campbell of the *Association for the Study of Peak Oil and Gas* (Campbell, Pers. Comm. 2006) noted that there are few reliable estimates of polar reserves, but "guessed" that ~5% of the world's oil is contained in the Arctic fields. Most production and transport from northern oil fields occurs in Arctic Russia and Alaska, although the Alberta oil fields of Canada could eventually prove to be substantial in global terms. Antarctic estimates vary even more wildly, from "poorly prospective, lacking effective source rocks" (Campbell, Pers. Comm. 2006), to reported figures of ~50 G barrels in the Ross and Weddell Seas (similar to Arctic reserves) or more (EIA 2000; Elliot 1988; Shapley 1974). Regardless, oil in Antarctica is unproven, and further exploration is prevented by moratorium.

Crude oil spills from ruptured pipelines in the Arctic are by far the largest sources of terrestrial petroleum pollution, followed by shoreline spills from tankers or resupply vessels. Diesel fuels are the next most common spills. Incidents are typically caused by infrastructure failure, human error during fuel transfer, "third party actions" (e.g. sabotage), or natural hazards. Risks are also known to be higher in some permafrost regions relative to non-permafrost regions within the same country (e.g. Russia (Det Norske Veritas 2003)).

1.2.1.1 Scale of the problem

There are currently insufficient data to define precisely the areal extent or volume of petroleum-contaminated soil in the cold regions. If we consider

[1] AMAP 1998 began their analysis of *Petroleum Hydrocarbons in the Arctic* by outlining the "reason for concern" (p. 661).

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the majority of cold regions soils as belonging to one of three broad geographic regions: Arctic/sub-Arctic, Antarctic/sub-Antarctic, and alpine, it is possible to compare selected case studies and get a sense of the scale of the problem. Assessing how much risk petroleum hydrocarbons pose to the various cold regions is more difficult.

To compare geographic regions or countries, a simple evaluation matrix has been compiled to assess the overall progress in the assessment and remediation of petroleum hydrocarbons in some reasonably well-documented sites (Table 1.1). The matrix is based closely on tables presented by the European Environment Agency – Indicator Management Service for Western Europe (EEA-IMS 2005). Reporting is known to be inconsistent between countries and discrepancies result because there is no international or even European consensus regarding legal standards for soil contamination. Only some of the European Union countries have legal standards, and national standards vary by country. The areal extent or volume of contaminated soil is also not often reported.

Whereas some data are available for the Arctic/sub-Arctic and Antarctic/sub-Antarctic, there is currently no synthesis on the extent of contamination in alpine regions, in particular the mid-latitude high-altitude regions, which are widely distributed. The data presented in Table 1.1, and discussed below, are therefore not specifically relevant to the Alpine regions.

1.2.1.2 Arctic

The Arctic Circle comprises the Arctic Ocean, Greenland, Baffin Island, other smaller northern islands, and the far northern parts of Europe, Russia, Alaska, and Canada. There is no consensus in this region on the response to petroleum hydrocarbon contamination and a direct comparison on the level of contamination is difficult. The definitive survey of pollution in the Arctic is the Arctic Monitoring and Assessment Programme (AMAP) Assessment Report of 1998. Much of the information in the report is now outdated, and AMAP are currently in the process of updating the petroleum hydrocarbon chapter (AMAP 2006). However, the 1998 report still offers the best overview of petroleum hydrocarbon contamination in the Arctic region, and it is used extensively in this summary. Below is a brief overview of the extent of contamination in most countries within the Arctic Circle as presented in Table 1.1.

Northern Europe: Finland, Norway, and Sweden

Although there is extensive reporting and coverage for Europe, petroleum hydrocarbon contamination in cold region soils are not specifically categorized. Overall, almost half of all European soil contaminants are petroleum hydrocarbons (20% oil, 16% PAHs, 13% BTEX, excluding chlorinated

Table 1.1 *Petroleum contaminated sites in cold regions or countries with a significant cold regions/permafrost presence. Some countries are not included due to insufficient data. The table structure closely follows the European Environment Agency – Indicator Management Service (EEA-IMS 2005) table on the progress in control and remediation of soil contamination. The numbers presented here are best estimates only*

Country	Preliminary study or investigation			Detailed site investigation			Implementation of remediation measures or development of a plan			Measures completed	
	Estimated total	Completed	%	Estimated total in need	Completed	%	Estimated total	Completed	%	Total	%
Finland[a]								292		1898	
Norway[a]		1521			277			43		246	
Sweden[a]	11 100	2960	12	4400	925	21	2960	185	6	444	15
Iceland[b]	>230	96	42								
Canada[c]	~2400										
Alaska	6400									3400	
Antarctica[d]	~200			~100	~8	30	10+	4		1	

[a] Estimated from EEA-IMS (2005) by multiplying the proportion of contaminated sites where the main contaminant was either mineral oil, BTEX, or PAH by the total number of sites registered.

[b] Environment and Food Agency Iceland (2002); Meyles and Schmidt (2005).

[c] The total estimated number of contaminated sites in Northern Canada (Yukon, Northwest Territories, and Nunavut) is estimated at approximately 2400. The primary source of contaminants at northern sites is petroleum hydrocarbons.

[d] Aislabie *et al.* (2004); Delille *et al.* (2006); Gore *et al.* (1999); Kennicutt (2003); Rayner *et al.* (2007); Revill *et al.* (2007); Roura (2004); Snape *et al.* (2006a); Stark *et al.* (2003).

hydrocarbons) (EEA-IMS 2005), and countries with substantial permafrost or cold soils have a similarly high proportion of petroleum contamination (Norway, 44%, Sweden, 37%, and Finland, 73%). Where known, the estimated number of petroleum-contaminated sites is shown in Table 1.1. When surveyed in 2004, most sites had not been assessed, and only a small proportion of those sites needing remediation had been completed. However, all three Scandinavian countries have ambitious targets for assessment and remediation (these targets are documented in the indicator table, EEA-IMS 2005).

Alaska

Most spills in Alaska are well documented. Many spills have been remediated, and many more are currently under investigation. Approximately 2000 spills per year are responded to, with most of these being cleaned up by the responsible party. A small percentage of these are of such magnitude that they become subject to long-term management and cleanup. A sizeable portion of the long-term remediation work deals with "legacy spills," typically associated with past handling practices that have led to the release of contaminants to the environment. As of June 30, 2006, approximately 6400 contaminated sites had been recorded in the Alaska contaminated sites database, of which approximately 3400 have been "closed."

Iceland

Cataloging of soil environmental problems has centered on soil erosion, and systematic data regarding soil contamination have been lacking. The European Environment Agency – Indicator Management Service (EEA-IMS 2005) estimated that in 2002 there were 100 contaminated sites in Iceland, but it is unclear how many of these sites are significantly contaminated with petroleum hydrocarbons. Preliminary investigations had been conducted on just five of these sites, and detailed site investigation and remediation had been completed on only three sites. No area or volumetric statistics were provided. The Icelandic Environment and Food Agency (UST) website estimates that over 200 fuel filling stations and about 30 fuel storage tanks are potential contaminated sites, accounting for approximately 25% of the contaminated soil in Iceland (Environment and Food Agency Iceland 2002). Meyles and Schmidt (2005) attempted to catalog contaminated soil sites throughout Iceland by surveying regional environmental agencies. They identified over 200 sites nationwide, 96 of which were filling stations and fuel storage tanks.

Canada

One major source of hydrocarbon contamination in the Canadian Arctic is associated with the early warning radar stations constructed across the Arctic during the Cold War. In 1985, an agreement between Canada and the United States was reached to replace the Distant Early Warning (DEW) line with a new satellite-based system and to clean up the old sites. Environmental assessments were conducted at all 42 DEW line stations between 1989 and 1993. The predominant contaminants identified were PCBs and metals (Poland *et al.* 2001; Stow *et al.* 2005). Hydrocarbons were not part of the original cleanup plans but were added at a later date. The contamination is well documented and both the Department of National Defence (DND) and Indian and Northern Affairs (INAC) maintain inventories of the sites for which they are responsible. Many sites have now been cleaned up. DND has completed ten of twenty-one DEW lines sites and INAC four of twenty-one sites.

Chronic spillage within human settlements is another major source of hydrocarbon contamination in the Canadian Arctic. For example, between 1971 and 2006, fuel spills reported in Iqaluit (Nunavut, Canada) totalled 627 000 L of diesel fuel while in Rankin Inlet, diesel fuel spills from tank farms accounted for 289 000 l. Most of these spills occurred during the 1970s and 1980s. During this period, environmental regulations were not as stringent as they are today, thus it is possible that a considerable quantity of fuel was never recovered or cleaned up to today's accepted standards.

Although there are few large mines in the Arctic, some abandoned older sites may have significant petroleum contamination present (e.g. Biggar *et al.* 2006). For example, at Nanisivik (North Baffin Island), it is known that 2000 drums of used oil were disposed of within a landfill. They have not been excavated and the mobility of this fuel is not currently known. For relatively newer operations, such as Polaris (near Resolute Bay), current regulations and water license conditions are such that any contamination would have been remediated before the site was "closed." Contamination associated with current mining operations is far more controlled and less likely to be a source of hydrocarbon contamination than activities associated with the communities.

In addition to these examples, Indian and Northern Affairs Canada (INAC) have identified ~800 sites that require cleanup. Hydrocarbon contamination is the main contaminant in the majority of these sites.

Russian Federation

Little accurate information is available for the Arctic, sub-Arctic, or alpine regions of the Former Soviet Union in the mainstream literature, but several case studies illustrate the scale of the petroleum pollution. The Komi oil spill of 1994 is perhaps the most infamous Russian oil spill and is regarded by some as one of the most serious environmental disasters of the last century (Bazilescu and Lyhus 1996). Following the rupture of an old degraded pipeline, oil (estimates[2] range from 14 000 tonnes to 240 000 tonnes, with a range of 37 000–44 000 tonnes most often quoted) poured across the Siberian tundra (areal estimates vary from 0.3 to 186 km^2) and into the Kolva River, a tributary of the Pechora River that flows into the Barents Sea (Bazilescu and Lyhus 1996; Wartena and Evenset 1997). Including chronic leakage until the mid 1990s, AMAP (1998) estimated the total discharge to be around 103 000–126 000 tonnes. The scale of this spill in comparison to all other world spills is staggering, but the surprising fact is not that it happened at all, but that the Komi spill is but one of many very large Russian oil spills. Det Norske Veritas (2003 p. 3) reported 113 major crude oil spills in the Former Soviet Union between 1986 and 1996 (with 17% in permafrost regions), but these "are widely thought to represent only a fraction of the total number of spills that occurred. Independent but unconfirmed sources indicate that some pipelines have experienced several hundred smaller spills." It is estimated that 20% of all oil that is pumped from the ground in Russia is lost through either chronic leakage or theft (Bazilescu and Lyhus 1996).

The accuracy of spill reporting in the Russian Federation is poor (Det Norske Veritas 2003). The Russian Minister of Natural Resources in the Komi Republic, Aleskandr Borovinskih, is quoted in the Bellona report of Feb 17, 2006 (Bellona 2006) as saying that oil companies often conceal spills. Alternatively, the extent of the spill is massively under-reported. In another case study described on the Bellona web site, an oil gusher occurred that reached 35–40 m into the air. The Natural Resource Ministry web site put the spill volume at 3000 tonnes (many times bigger than the much publicized "largest" Alaska Pipeline spill of ~700 tonnes in March 2006, discussed below). In contrast, Transneft, the company responsible for the oil gusher, estimated the spill to have been only 10 tonnes. The Regional Environment Oversight Agency agreed with the Natural Resource Ministry that the spill was many times greater than the estimate provided by Transneft.

Given the poor level of reporting, it is not possible to estimate reliably the volume of petroleum hydrocarbon contaminated soil in Russia. Many incident reports describe hectare-scale contamination (see Bellona.com), or polluted rivers or plumes that extend hundreds of kilometers. AMAP (1998) noted that almost all water samples taken in a regional survey of northwest Siberian Rivers exceeded

[2] Several of the most widely available sources of Russian information are from non-government organization or US websites. The authors were unable to verify the accuracy of such non-peer reviewed sources.

the maximum permissible concentration of 0.05 mg total petroleum hydrocarbons l^{-1}. A few incidents are reported where contamination is in the region of kilometers square in size, and one or two in the range of 10s–100s km^2. Based on available information, it is not possible to reliably estimate the extent of contamination. Extrapolating from what information is available, we speculate that the total amount of petroleum-contaminated permafrost in Russia could be somewhere in the region of 1–10 billion m^3. If the area of Arctic and sub-Arctic Russia is taken as ≈6 million km^2 (AMAP 1998), that would equate to $\approx 10^{-3}$–10^{-4}% of this type of terrestrial habitat contaminated with petroleum products. However, this figure seems very low, given the reported extent of water contamination noted above.

1.2.1.3 Antarctic

The Madrid Protocol prohibits all Antarctic Treaty member nations from mineral resource activities in Antarctica, including oil exploration and exploitation (Rothwell and Davis 1997). As a result the extent of petroleum contamination is very low in absolute terms, and the Antarctic and sub-Antarctic are undoubtedly the least polluted cold regions in terms of total area polluted, volume spilled or volume/mass of soil/water contaminated. Spills are mostly of kerosene, Antarctic blend or similar light diesel.

In common with the Arctic region there are many countries responsible for petroleum hydrocarbon spills within the Antarctic/sub-Antarctic region. Forty-five countries are signatories to the Antarctic Treaty and 28 of these are Consultative Parties (i.e. may participate in any decision-making process). Reporting requirements for fuel spills have only been required of these signatories since 1998 and documentation for prior spills was country dependent.

Spills near Australian Antarctic stations or sub-Antarctic Islands are generally well documented. Six fuel plumes known from the Australian Casey Station and Macquarie Island areas have been fully evaluated and are scheduled for remediation as part of a national program of works (Rayner *et al.* 2007; Snape *et al.* 2005; Snape *et al.* 2006a). An additional area of chronic spillage (i.e. many small spills) at the abandoned Wilkes Station is partly evaluated (Snape *et al.* 1998). World Park Base operated by Greenpeace has been fully remediated and well documented (Roura 2004). Spills near the New Zealand, French and Argentine stations are typically partly documented to well documented (e.g. Aislabie *et al.* 2004; Delille *et al.* 2006; Waterhouse and Roper-Gee 2002). Many spills under the jurisdiction of the US program are partly documented (Kennicutt 2003; Klein *et al.* 2006), although some have been more fully evaluated, have been remediated, and are well documented (Christensen and Shenk 2006; Kennicutt 2003). The 2003 report on human disturbance at McMurdo Station (by far the largest station in Antarctica) noted 385 spills between 1991 and 2000, mostly of JP8, totalling ~80 000 l. Several larger spills are known from the 1970s and 1980s, including a spill of 260 000 l in 1989 (Kennicutt 2003). Little widely published information is available for fuel spills near Japanese, Chinese or Russian stations. Many of these spills are either not systematically or reliably documented, or only some aspects of spill evaluation have been published and are partly documented (e.g. Goldsworthy *et al.* 2003).

Taken at the largest geographic scale, the Antarctic/sub-Antarctic region is at best partly documented. Most spills are not accurately delineated, and estimating the extent of petroleum contamination from such a patchy dataset is difficult. Nevertheless, an order-of-magnitude has been estimated. Where a spill has been reported or there is a picture of a spill, it has been assumed that the spill reached a depth of 1 m on average (Revill *et al.* 2007; Snape *et al.* 2006a). Where a station has recorded no spill history, but there is anecdotal evidence of contamination, the authors assumed that the extent of contamination was similar to other well-documented stations of similar size. There are approximately 65 stations distributed around the continent (COMNAP 2006), and there is perhaps a similar number of large field camps. Assuming most stations and field camps have some fuel contamination, it can be best estimated that there are 100 000 to 1 million m^3 of soil contaminated[3] at a concentration >100 mg fuel kg^{-1} soil.[4] If the vast glaciated regions are excluded and contamination is considered as a proportion of terrestrial habitat with soil and significant ecosystem development, that equates to $\approx 10^{-3}$% of the ~6000 km^2 of ice-free coastal habitat (Poland *et al.* 2003).

1.2.1.4 *Summary of the extent of contamination in cold regions*

The degree of contamination in cold regions is difficult to assess as the level of documentation is country specific. Even in the Antarctic, where waste is managed under a common international environmental protocol (Madrid Protocol), variation between countries on their reporting of historic spills (prior to 1998) varies greatly. Generally, spills of petroleum hydrocarbons tend to be well documented in developed countries and response to spills more clearly defined when compared to less-developed countries. For perspective, Russian oil spills are categorized on a three-level scale: Localized spills (up to 500 tonnes), regional level spills (500–5000 tonnes) and federal level spills (>5000 tonnes)

[3] Based on observation of fuel spills at Casey Station, Antarctica, every 1 kg of fuel spilled creates between 100 to 1000 times that amount of contaminated soil by mass. This observation is the same order-of-magnitude estimate that we can infer from the AMAP oil spill migration model (AMAP 1998, p. 676).

[4] Note: all soil concentrations throughout this chapter are presented as dry mass.