# The use of remote sensing technology to delineate hydrocarbon contamination in the Arctic

M.K. Blade, & H.D. Ziervogel
*EBA Engineering Consultants Ltd., Edmonton, Alberta, Canada*

ABSTRACT
Biodegradation of organic contaminants, typically diesel, in Arctic regions causes biogeochemical changes in ground and surface water, resulting in increased dissolved constituents and favourable environments for microbial mat growth. These areas are often dominated by *Oscillatoria sp*. and *Phormidium sp*., along with mosses and cotton grass, *Eriophorum callitrix*, at groundwater and surface water interfaces.

Multispectral satellite imagery is used to map contamination by locating the reflectivity and absorption spectra of diesel and associated plant species and plotting the corresponding spatial distributions. Resulting maps are used for non-intrusive identification and prioritization of contaminated sites in remote and/or sensitive environments, such as those containing permafrost in the Arctic.

RÉSUMÉ
Dans des régions arctiques, la biodégradation de polluants organiques (typiquement le diesel) produisent des changements biogéochimiques affectant l'eau de surface et la nappe phréatique. L'augmentation de la teneur en substances dissoutes contribue à la communauté d'une natte microbienne qui est souvent dominée par *Oscillateria sp*. and *Phormidium sp*., avec des mousses et la linaigrette à belle crinière (*Eriophorum callitrix*), aux lieux où l'eau de surface et la nappe phréatique s'interfacent.

Des images satellites multispectrales sont utilisées pour identifier les endroits contaminées en observant la réflectivité et les spectres absorbants de diesel et végétation associée, et en traçant les distributions spatiales correspondantes. Les cartes graphiques résultantes sont utilisées pour l'identification et la priorisation de sites contaminés par des méthodes non invasive dans les environnements isolés et sensibles, comme les zones de pergélisol de l'Arctique.

## 1 INTRODUCTION

Development of the Canadian Arctic was limited before the 1940s, but increased considerably at the beginning of the Cold War era, resulting in the building of Distant Early Warning (D.E.W.) radar sites and military bases, such as the Upper Base Airstrip found at Resolute Bay, NU. Development, along with increased interest in resource extraction in the late 1960s and early 1970s, resulted in contamination from petroleum hydrocarbons (PHC), polychlorinated biphenyls (PCBs), and metals. Much of the contamination has been from diesel spills, used as the primary source of fuel for generating stations, heating fuel and for fuel for transportation. Spills, resulting in PHC contamination of the surface and subsurface, were very common until the 1990s when fuel distribution systems were upgraded (Poland et al, 2000). Assessment of these contaminated facilities began in the 1990s, but associated costs are high. The use of remote sensing may provide a cost-effective way of screening and prioritizing these sites.

## 2 LITERATURE REVIEW

Determining the extent of hydrocarbon contamination typically involves intrusive soil sampling, but an understanding of biogeochemical processes may allow inference of contamination through non-intrusive means, such as remote sensing. The use of non-intrusive means can be advantageous and a desirable alternative in the high Arctic where the cost of sampling is greater. Geochemical changes in the subsurface, that result from hydrocarbon biodegradation lead to changes in biogeochemical surface expression. These changes could be detected through use of remote sensing, as previously achieved in the Siberian tundra, to detect vegetation damage caused by industrial impacts (Toutoubalina et al, 1999).

Carbon, oxygen and hydrogen cycles are driven by two energy pools. First, photosynthetic fixation of organic matter from carbon dioxide, a process which does not occur in the subsurface; and second, oxidation of organic matter back to carbon dioxide, a process that in the subsurface leads to depletion of oxygen and accumulation of carbon dioxide and carbon dioxide-derived carbonate species in groundwater (Chapelle, 2000). A large diesel spill in an oligotrophic, nutrientpoor environment, such as the high Arctic, represents a large energy pool of organic matter. Biodegradation of the diesel result in increased carbon dioxide concentrations and carbonate alkalinity in the shallow groundwater, with the resulting carbon dioxide lowering the pH of the groundwater. Biodegradation also lowers oxygen concentrations in the groundwater allowing anaerobic processes (such as iron and sulfate reduction) to occur, resulting in increased dissolved iron and sulphide concentrations, and lower sulphate concentrations (Wiedemeyer et al, 1999).

When petroleum hydrocarbon concentrations are low (approximately 1,000 mg/L), early researchers noted increased populations of cyanobacteria and coccoid green algae and increased algal diversity (Snow et al, 1975). At higher PHC concentrations (approximately 10,000 mg/L), early researchers observed increases in the diatom population but decreases in coccoid green algae population (Atlas et al, 1975). A portion of the increase in cyanobacteria, algae, and diatoms biomass was attributed to toxicity of the spills to zooplankton, reducing grazing (Miller et al, 1978).

Microbial mats dominated by cyanobacteria in proximity to oil spills have been reported (Al Hassan et al, 1993, Abed at al, 2002), including in the Arctic (Ziervogel et al 2003). These microbial mats have a yellow or brown surface layer of diatoms with filamentous or unicellular cyanobacteria, and deeper layers of green, purple and black colouration by filamentous blue-green, purple and green sulphur bacteria and by black iron sulphide deposits (Fenchel et al, 1998). In extreme environments, such as the high Arctic, biomass decrease due to grazing metazoans and eukaryotic organisms is eliminated from the microbial mats (Cohen, 1990). These environments are symbiotic and synergistic with nitrogen fixing, microaerophilic and anaerobic microzones (Paerl et al, 1995) and the trapping of sulphide, through precipitation of FeS, allowing diatoms to form at surface (Cohen, 1990).

The microbial mats in the Arctic, Subarctic and Antarctic are dominated by the genus Oscillatoria or *Phormidium* (Tang et al, 1997). While these genii are not genetically adapted for the Arctic, they tolerate desiccation, freeze-thaw, and continuous solar radiation. *Phormidium* resumes photosynthesis and respiration immediately upon thawing (Davey, 1989).

Plant species may be less tolerant to diesel contamination than microbial mats; grasses show intolerance to high concentrations of PHC contamination, and variance in germination rates dependant on diesel concentration (Adams et al, 2004). Mosses and lichens are variably intolerant to organic contaminants and are excellent indicators of the extent and degree of contamination present (Zechmeister et al 2007).

In areas with high PHC concentrations, the biological communities are expected to be dominated by diatoms with low populations of cyanobacteria and other algaes. The overall biodiversity is low. As concentrations of PHCs decrease to below 1,000 mg/L, algae and cyanobacteria diversity and populations should increase. In areas with low to no hydrocarbon impacts, but a nutrient-rich groundwater plume resulting from nearby biodegradation processes, eutrophic conditions should produce greater biological diversity. Species in these areas, especially seep areas, would include mosses and grasses, along with increased algal and cyanobacteria diversity.

Using remote sensing as a tool, these differences in Arctic freshwater vegetation could be used to infer and even crudely delineate contaminant impacts visually. Satellite imagery could be used to detect differences in both the diversity and species of plants, algae, cyanobacteria and diatoms, as well as the nutrient effects of biodegradation by-products could be detected which suggest contamination.

## 3 ENVIRONMENTAL SITE ASSESSMENT OF RESOLUTE BAY AIRSTRIP

Site assessments of the former upper military base facilities at Resolute Bay, NU (Figure 1) were conducted in 2003 to determine the extent of contamination at tank farms and fuel distribution networks throughout the site (EBA, 2003).

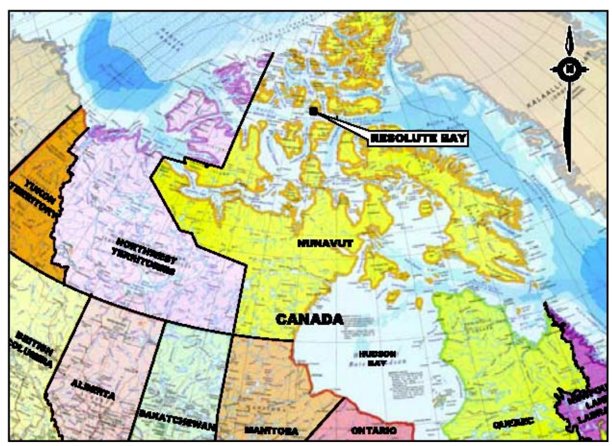

Figure 1. Resolute Bay on Cornwallis Island in Nunavut, Canada

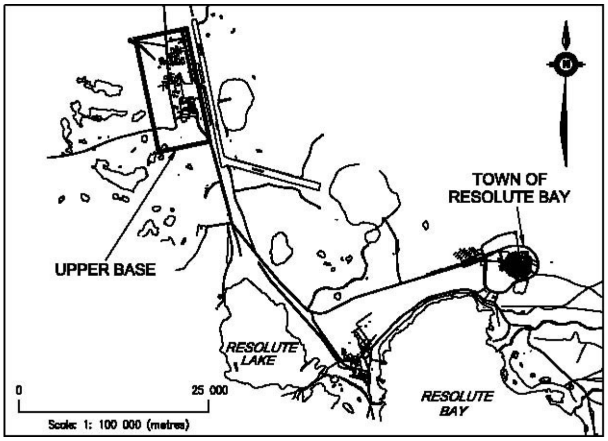

Figure 2. Upper Base Resolute Airstrip near Town of Resolute Bay, NU

Resolute Bay had a weather station established in 1947 and an airbase built in 1949. The current airport and former military facilities, now mostly derelict, are referred to as Upper Base and are separate from the town Resolute Bay (Figure 2). The Upper Base fuel facilities were built when the military facility was established, and numerous large fuel spills have been reported at this location.

Assessment of the Upper Base included testpitting, and a soil and water sampling program. Soil was tested for total PHCs using Petroflag test kits on site. Soil was tested for total extractable and volatile hydrocarbons, benzene, toluene, ethylbenzene and xylenes in a laboratory environment. Water was tested for total alkalinity, expressed as carbonate alkalinity, and carbon dioxide and sulphides using chemetrics titre. Other tests included dissolved oxygen, dissolved iron, sulphates, nitrates and ammonia, which were completed using a colorimeter.

Generally, where PHCs are present there is a greater concentration of carbon dioxide and total alkalinity (Figure 3). Higher concentrations of dissolved iron, sulphides, nitrates and ammonia were also found to be higher within PHC impacted areas compared to non-impacted areas, and generally correlated well with PHC concentrations.

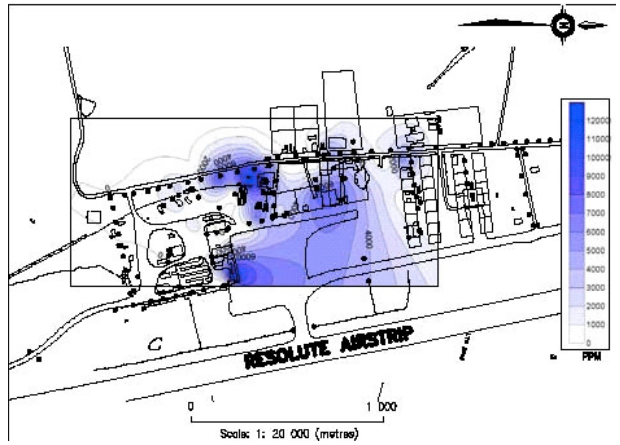

Figure 3. Total petroleum hydrocarbon concentrations in soil at Upper Base Resolute Airstrip, NU

Dissolved carbon dioxide concentrations spatially match contours for total PHC concentrations, but also show a slightly larger extent than the PHC contaminated area (Figure 4). Dissolved carbon dioxide concentrations could be elevated in areas surrounding PHCs because PHC biodegradation result in increased nutrient concentrations from dissolved constituents in groundwater, which extend beyond the PHC impacted areas.

Elevated nutrients were noticed at numerous locations throughout the Upper Base during the 2003 field season. Within areas of high concentrations of PHCs, surface coloration was primarily thin reddish brown with underlying black sulphide deposits. Further afield, again in hydrocarbon impacted areas but with lower concentrations, obvious filamentous green and brown algae were present, along with underlying sulphide deposits. Mosses were found growing just outside of the area of low hydrocarbon concentrations but within the nutrient halo, along with microbial mats. Characterization of these mats found they were dominated by *Oscillitaria nigra voucher* and *Phormidum sp*, along with numerous diatom species and two algaes, *Microspora sp* and *Geminella sp*. (Ziervogel et al, 2003).

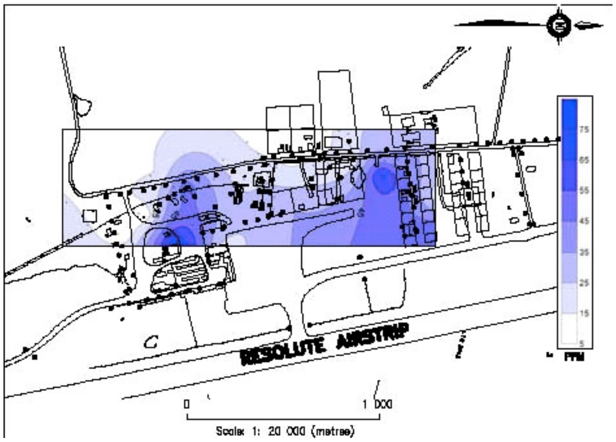

Figure 4. Carbon dioxide concentrations in water at Resolute Airstrip, NU

## 4 METHODS

Standard ortho-ready Quickbird satellite imagery were obtained from MDA geospatial services at a 16 bit depth for the 15 July 2002, one year prior to the 2003 environmental site assessment of the Upper Base. Due to cloud and snow cover, 2003 satellite imagery were not viable for analysis. The satellite imagery used contain both panchromatic files at a 60 cm ground sample distance, and four-band multispectral files at a 2.4 m ground sample distance. To reduce post imagery acquisition pixel blending, a nearest neighbour resampling kernel was chosen.

The four-band multispectral files consist of four isolated wavelengths: red (650 nm), green (510 nm), blue (475 nm), and near infrared (NIR) (750-1,400 nm). Unique wavelength intensity values were developed for each of the four bands for the satellite image. The total number of intensities for each band are summarized in Table 1.

Table 1. Total number of unique wavelength intensity values for the 15 July 2002 satellite image with four multispectral bands near Resolute, NU.

| Wavelength | Number of Unique Value Intensities for the 15 July 2002 Satellite Image near Resolute, NU. |
|---|---|
| Red | 1,159 |
| Green | 1,776 |
| Blue | 1,336 |
| NIR | 1,168 |

By determining the wavelength intensity of the four bands over a known ground-truthed area from the 2003 environmental site assessment, a classification scheme of the land surface is generated using the raster calculator extension in geographical information systems (GIS). The classification scheme is then applied to the remainder of the satellite image to increase knowledge of the land surface in areas not part of the 2003 site investigation.

## 5 RESULTS

Examination of the unique value intensities of the four multispectral bands in areas of known land surface type indicate specific intensity ranges associated with each surface classification. For example, snow and ice, present in the centre of the lake east of Resolute Airstrip are highly reflective and therefore have greater intensity in all four bands (Figure 5).

Figure 5. Microbial mat and Bryophyte ground-truthed locations during 2003 environmental site assessment

Water, in comparison, is highly absorptive of all four wavelengths, registering low in intensity for all four bands.


Figure 6. Microbial mat west of Resolute Airstrip, NU

Microbial mats, located west of the Resolute Airstrip, are reddish green in colour and have both upper and lower boundaries in intensity range for all four bands (Figure 6). Compared to bryophytes and grasses present on site, microbial mats register higher in intensity in all four bands, but have a lower intensity than snow and ice.

Figure 7. Bryophytes southwest of Resolute Airstrip, NU

Bryophytes (Figure 7), located southwest of the Resolute Airstrip, and native grasses (Figure 8), surrounding a Thule site south of Resolute Lake, have similar low intensity ranges in the red, green, and blue bands. In the NIR band, bryophytes have an intensity between 265 and 388, whereas native grasses have an intensity between 388 and 500, making them distinguishable via remote sensing.

Figure 8. Native grass surrounding Thule site south of Resolute Lake, NU

The unique value intensity ranges for all four isolated multispectral bands near the Resolute Airstrip, NU, based on surface classification, are summarized in Table 2.

Table 2. Unique value intensity ranges for all four isolated multispectral bands near the Resolute Airstrip, NU based on land classification.

| Classification | Red | Green | Blue | Near Infrared |
|---|---|---|---|---|
| Ice and Snow | >429 | >653 | >498 | >550 |
| Water | <313 | <433 | <275 | <232[1] |
| Microbial Mats | 291-359 | 424-543 | 341-454 | 416-455 |
| Bryophytes | <280 | <423 | <305 | 265-388 |
| Native Grasses | <280 | <423 | <305 | 388-500 |

[1]Only the NIR intensity value was used in the raster classification calculation for water.

## 6 INTERPRETATION

Searching for the unique value intensity ranges determined for ice, microbial mats, bryophytes, and grasses in the satellite image near Upper Base identified additional potentially contaminated areas, unable to be visited and characterized during the 2003 environmental assessment, based on the four-wavelength intensity surface classification scheme summarized in Table 2.

Ice and snow wavelength intensities are located at the centre of Strip Lake, east of the Resolute Airstrip (Figure 9). Additionally, highly reflective roofs within the Upper Base site are also classified as ice and snow, most likely a result of the building material reflectivity.

Microbial mats, that correspond with PHC concentrations greater than 1,000 mg/L, and were identified during the 2003 environmental site assessment to the west of the tank farm (Figure 5), match the four-wavelength intensity surface classification in additional areas south, east, and west of the site, as well as within the facilities of the Upper Base site themselves (Figure 6).

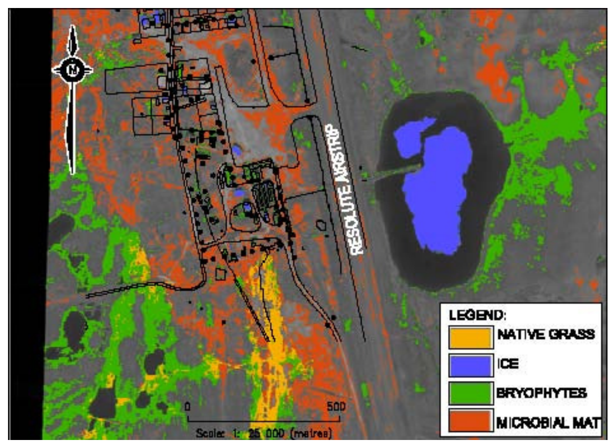


Figure 9. Land surface classification of the upper base Resolute Airstrip, NU site based on four wavelength intensities

The microbial mat classification areas are discontinuous, most likely due to the 2.4-metre pixel resolution of the multispectral data. For remote sensing detection and classification, the surface water and subsequent microbial mat growth need to cover at least 2.4 metres square, and not be mixed with other land surface classifications. Additionally, microbial mat classifications may be discontinuous due to the sand and gravel used to grade the site having a similar four-wavelength intensity ranges as the microbial mats making distinguishing of each difficult.

Bryophytes and native grasses, that correspond with PHC concentrations less than 1,000 mg/L, extend further from the site than the microbial mats associated with PHC concentrations greater than 1,000 mg/L, indicative of decreasing PHC concentrations with distance from the site. Bryophytes are located southwest of the site, and east of Strip Lake where barrels are rumoured to have been stored but access was not granted during the 2003 environmental site assessment. Native grasses follow a surface drainage passage from the site to the south.

Areas not characterized as one of the land surface classifications are left blank.

When the classification scheme is applied to the entire satellite image, snow and ice, as seen in Figure 10, are in the centre of most lakes with water exposed along the lake perimeters. Microbial mats, that can be associated with PHC concentrations greater than 1,000 mg/L, are north, south, east, and west of the Upper Base site (Figure 10). To the south, the microbial mats have the furthest extent most likely following surface and groundwater seep flow patterns towards Resolute Lake, and beyond to Resolute Bay south of the site.

Bryophytes, thought to thrive in nutrient rich areas in the high Arctic from biodegradation of PHC concentrations less than 1,000 mg/L, are growing east, west, and south of the site (Figure 10), mainly in areas surrounding lakes. Near the site, bryophyte growth may be associated with nutrients generated during PHC biodegradation; however, in areas surrounding lakes, bryophyte growth may be occurring from surface water runoff and subsequent deposition of nutrient rich suspended material near lake areas.

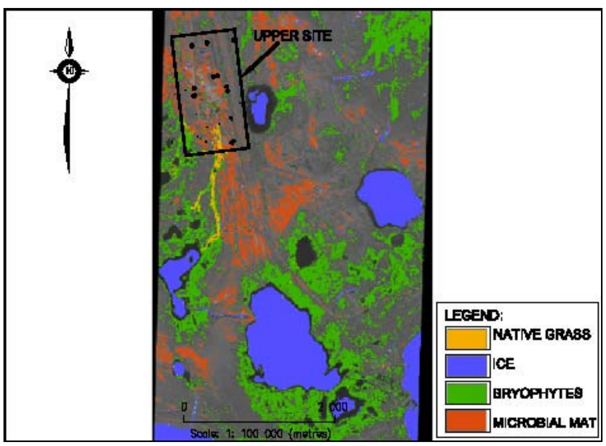


Figure 10. Land surface classification of Resolute, NU satellite image based on four-band wavelength intensities

Native grasses are seen south of the Upper Base site in a surface drainage passage flowing to the southwest to Meretta Lake, NU (Figure 10). Native grasses have a low to no tolerance for PHCs, however, will grow well nearby nutrient rich areas where biodegradation processes have already occurred. The native grasses located in the surface drainage passage commencing at the upper base site may be the result of nutrients from biodegradation processes on site entering the surface drainage passage and enhancing native grass growth.

## 7 CONCLUSIONS

Interest in the Canadian Arctic has resulted in the building of D.E.W. radar sites and military bases, such as the Upper Base Airstrip found at Resolute Bay, NU. Development has brought along contamination by PHCs, mainly in the form of diesel, used for powering generating stations, and in heating and transportation. Geochemical changes in the subsurface, that result from PHC biodegradation, could conceivably lead to changes in surface expression. Recently, researchers have noted microbial mat growth, dominated by the genus *Oscillatoria* or *Phormidium,* where PHC concentrations exceed 1,000 mg/L, and bryophyte and native grass growth where PHC concentrations are less than 1,000 mg/L. These differences in Arctic freshwater vegetation can be used to infer and even crudely delineate contaminant impacts visually by using remote sensing as a tool. Through raster spatial analysis of red, green, blue and NIR wavelength satellite imagery in GIS, unique value intensity ranges were identified for all four wavelengths for each Arctic freshwater vegetation type based on the 2003 ground-truthed environmental vegetation and geochemical assessment locations. When applied to the entire satellite image, additional areas of potential contamination were identified that were inaccessible during the 2003 site visit. Limitations of remote sensing detection include the 2.4 metre pixel resolution and the number of wavelengths available for analysis. With finer pixel resolution, and greater number of wavelengths available specific to Arctic freshwater vegetation spectral signatures, greater inference and delineation of contamination in the high Arctic can be achieved.

## 8 ACKNOWLEDGEMENTS

The writers would like to acknowledge the support provided by EBA Engineering Consultants Ltd.

## 9 REFERENCES

Adams, G. and Duncan, H.J., 1999, Effect of diesel fuel on growth of selected plant species, Environmental Geochemistry and Health, Volume 21, Number 4, pp 353-357.

Abed, R.M.M. Safi, N. Koster, J. de Beer, D. El-Nahhal, Y. Rullkotter, J. Garcia-Pichel, F. 2002. Microbial Diversity of a Heavily Polluted Microbial Mat and Its Community Changes following Degradation of Petroleum Compounds. Applied and Environmental Microbiology. Volume 68 No. 4. American Society of Microbiology: 1674-1683.

Al Hassan, R.H. Sorkhoh, D. Al Bader, S. Radwan, S.S. 1993. Utilization of hydrocarbons by cyanobacteria from microbial mats on oily coasts of the Gulf. Applied Microbiology and Biotechnology. Volume 41 Issue 5. Springer-Verlag: 615-619.

Atlas, R.M. Schofield, E.A., Morell: F.A. & Cameron, R.E. 1976. Effects of Petroleum Pollutants on Arctic Microbial Populations. Environmental Pollution (10). Applied Sciences Publishers Ltd., Great Britain: 35-43.

Chappelle, F.H. 2001. Groundwater Microbiology and Chemistry, 2nd Ed. John Wiley and Sons, New York.

Cohen, Y. 1990. Photosynthesis in Cyanobacterial Mats and its Relation to the Sulfur Cycle: A Model for Microbial Sulfur Interactions. Cohen, Y. & Rosenberg E. (Ed.) Microbial Mats: Psychological Ecology of Bathic Microbial Communities. American Society for Microbiology, Washington, D.C.: 22-36.

Davey, M.C. 1989. The effects of freezing and desiccation on photosynthesis and survival of terrestrial AntArctic algae and cyanobacteria. Polar Biology 10: 29-36.

EBA Engineering Consultants Ltd. 2003, Environmental Site Assessment, Resolute Bay.

Miller, M. Alexander, V. Barsdate, J. 1978. The Effects of Oil Spills on Phytoplankton In An Arctic Lake and Ponds. Arctic Volume 31, No. 3. 192-218.

Paerl, H.W., Pinckney, J.L., 1996. A Mini-review of Microbial Consortia: Their Roles in Aquatic Production and Biogeochemical Cycling, Microbial Ecology (31) Springer-verlag, New York Inc.: 225-413.

Poland, J.S, Mitchell, J., and Rutter, A., 2001, Remediation of Former Military Bases in the Arctic, Cold Regions Science and Technology, Volume 32, Issues 2-3, pp. 93-105.

Snow, N.B, and Rosenburg, D.M., 1975. Experimental Oil Spills on Mackenzie Delta Lake, II Effects of Two Types of Crude Oil on Lakes 4C and 8. Fish. Mar. Serv. Res. Dev. Tech. Report 549.

Toutoubalina, O.V., Rees, R.V., 1999, Remote Sensing of Industrial Impact on Arctic Vegetation around Noril'sk, Northern Siberia, Preliminary Results, International Journal of Remote Sensing, Volume 20, Issues 15-16, pp 2979-2990.

Tang, E.P.Y., Tremblay, R. and Vincent, W.F. 1997. Cyanobacterial dominance of polar freshwater ecosystems: are high-latitude mat-formers adapted to low temperatures? Journal of Psychology 33: 171-181.

Wiedemeyer, T.H., Wilson, J.T., Kambell, D., Miller, R.N., Hansen, J.E., 1999, Technical Protocal for Implementing Intrinsic Remediation with Long Term Monitoring of Fuel Contamination Dissolved in Groundwater, Air Force Centre for Environmental Excellence.

Zechmeister, K.G., Grazyna, S. 2007, Trace Metals and Other Contaminants in the Environment, Vol 6, pp 329-375.

Ziervogel, H., Nelson, J.A., Murdock, E., Selann, J., Diatom, Cyanobacterial and Microbial Mats as Indicators of Hydrocarbon Contaminated Arctic Streams and Waters, 2003, Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates '03 Conference Proceedings, pp 93-102.