



Effects of fuel spills on Arctic soil, 32 years later (Hornsund, Svalbard)

Anna J. KRZYSZOWSKA WAITKUS* and Brian WAITKUS

Environmental Consulting, 80 Eagle Nest Ln., Laramie, WY 82070, USA

* *corresponding author <enviro@wyoming.com>*

Abstract: The purpose of the study was to estimate in 2012 range and degree of soil contamination due to local diesel fuel leakage spills that occurred in 1980 and from any subsequent activities in the vicinity of the scientific Polish Polar Station in Hornsund, Svalbard. The area of the study covered the immediate vicinity of station buildings including areas of the 1980's fuel barrel storage depot and location of current fuel tanks. Results of the study were compared with a similar study performed in 1980. As of 2012, areas potentially contaminated covered 0.9 ha, which was a 50% decrease compared to 1980. The area contaminated with total petroleum hydrocarbons was extremely localized. Spread of petroleum hydrocarbons from 1980's source of pollution investigated 32 years later showed that petroleum derived products were environmentally mobile. Concentrations of total petroleum hydrocarbons in surface soils of the unsaturated active layer above the permafrost decreased significantly mostly due to surface runoff and dispersion through ephemeral drainages. Concentrations of total petroleum hydrocarbons increased with depth through time in sandy soils on the flat area where the largest 1980's fuel barrel depot was located.

Key words: Arctic, Spitsbergen, Polish Polar Station, soil pollution, total petroleum hydrocarbons, dissipation rate.

Introduction

Petroleum hydrocarbon contaminations due to local fuel spills is one of the most common impacts of the polar research station's activities (Krzyszowska 1981, 1985, 1989, 1990, 1993; Krzyszowska Waitkus 1997; Shears *et al.* 1998; Poland *et al.* 2003; Goldsworthy *et al.* 2003). Usually this is caused by a cumulative impact of on-going activities from routine operations involving uses of diesel engines, vehicles etc. Oil contamination and their derivatives persist in arctic soils for long periods because of a slow degradation rate due to low



temperatures combined with low nutrient content, low solubility, and reduced volatility of hydrocarbons in cold climates (Linkins *et al.* 1984; Atlas 1986; Eriksson *et al.* 2001; Børresen *et al.* 2003; Yang *et al.* 2009; AMAP 2010). However, little is known on the longevity of petroleum hydrocarbon contaminants in the Arctic over a period of years from the time of the spill (Everett 1978; Sextone *et al.* 1978; Collins *et al.* 1993; Kachinskii *et al.* 2014). Very few studies compared concentrations of petroleum hydrocarbons in tundra soils between the original measurements after the fuel spill with concentrations found decades later in similar location (Krzyszowska Waitkus 1997). The opportunity to perform a study of soil contaminations around the Polish Polar Station in Hornsund, Svalbard in 2012, and comparing these results with a similar study performed in 1980 (Krzyszowska 1985, 1986), provided an excellent insight into petroleum hydrocarbons behavior in tundra environment after 32 years.

Transportation and fates of oil spills in tundra are influenced by numerous factors such as oil composition, spill volume, and environmental conditions including type of soil, vegetation cover, permafrost depth, and topography (Barnes and Filler 2003; AMAP 2010; Kachinskii *et al.* 2014; Filler *et al.* 2015). Once in soil, degradation processes including leaching, biodegradation, adsorption, and accumulation affect concentrations of petroleum hydrocarbons in cold climate soils (Margesin and Schinner 2001; Rike *et al.* 2003, 2008). Individual effects from these processes were not separated in the current study and results represent the cumulative effect of the dissipation rate of petroleum hydrocarbons in a tundra environment after 32 years.

Material and methods

Soil samples were collected in the vicinity of the scientific Polish Polar Station (currently the Stanisław Siedlecki Polish Polar Station in Hornsund), located in the West Spitsbergen Island, Hornsund fiord of the Isbjørnhamna bay (77°0' N, 15°33' E). The station is located on an upper sea terrace at 10 m a.s.l., just above an escarpment of 3 m in height, at 200 m distance from the sea coast (Birkenmajer 1960). Since 2003, diesel for the power station has been stored in four double walled fuel tanks (25 m³ each), while a fifth tank has been used as an emergency tank. Fuel tanks are located on the lower sea terrace at 4 m a.s.l., near the harbor. In 1980, fuel was stored on the upper sea terrace, at the main fuel barrel depot (storage area of 40 m × 15 m) located 50–80 m north of the power station (Krzyszowska 1986). Another smaller temporary fuel barrel storage area (storage area of 25 m × 6 m) in 1980's was located adjacent to north side of the summer residential/laboratory building, just above the escarpment. All fuel barrels were removed by 2004 with the majority being removed in 2003.

Soil samples were collected from the unsaturated active layer above permafrost in the summer of 2012. They were located on the upper sea terrace consisting of coarse and medium sand with weathered rock, the lower sea terrace built of sand and gravel, and the beach built of sand and pebbles. Soils here are characterized as in initial stages of development with low content of organic matter (Ziaja and Skiba 2002). A total of 59 soil samples were collected between July 25 and August 4, 2012, including 25 surface soil samples (at depths of 0–2 cm) and nine soil profiles, containing a total of 34 individual soil samples from depths of 0–2, 2–5, 5–10, 10–20, and 20–30 cm (Fig. 1 and Table 1). Included in this group of samples were 11 surface soil samples and seven soil profiles (total of 28 samples) collected from locations corresponding to the 1980 sites. All samples were sieved through a two mm stainless steel sieve, and approximately 50 g of each sample was frozen for later analysis. Precautions were taken to avoid cross contamination between samples collected in the field and during sample preparation.

All soil sample collection sites were located on a topographic map in the scale of 1:5000 (see Dąbrowski 1985, enclosure 1). The map was georeferenced using Geographic Coordinate System: UTM (Universal Transverse Mercator); Zone: 33 North; and Datum: WGS 1984 (World Geodetic System of 1984). Georeferencing was performed using Esri's ArcGIS Geographic Information System (GIS) ArcMap 10 software. After georeferencing was completed, maps with 1980 site locations were installed on a Trimble GeoExplorer Series GPS, GeoXM unit. This allowed collecting soil samples from similar locations as those collected in 1980 and linked collected soil samples datasets with their geographic locations.

Soil samples were analyzed for concentrations of Diesel Range Organics (DRO) of Total Petroleum Hydrocarbons (TPH) that were absorbed into soil. There was a need to check if the naturally occurring organic matter interfere with TPH in fuel oil contaminated soil samples (White *et al.* 2008). A silica gel cleanup was implemented to remove polar fractions of naturally occurring hydrocarbons. Throughout this article, concentrations of DRO (nC_{10} – nC_{32}) are labeled Total Extractable Hydrocarbons (TEH) before silica gel cleanup and Total Petroleum Hydrocarbons (TPH) – after cleanup, in soil samples collected in 2012.

Soil samples were analyzed by a certified subcontracted laboratory, Inter-Mountain Laboratories, Inc. in Sheridan, WY (USA). The laboratory used methods according to the U.S. Environmental Protection Agency Method (EPA) (US EPA 2007). Samples were extracted using an ultrasonic extraction method according to EPA Method 3550B, Ultrasonic extraction (US EPA 2007). A silica gel clean-up for removal of naturally occurring hydrocarbons (polar compounds) was implemented according to EPA Method 3630C, Silica gel cleanup (US EPA 2007). Both extracts, before and after silica gel cleanup, were analyzed

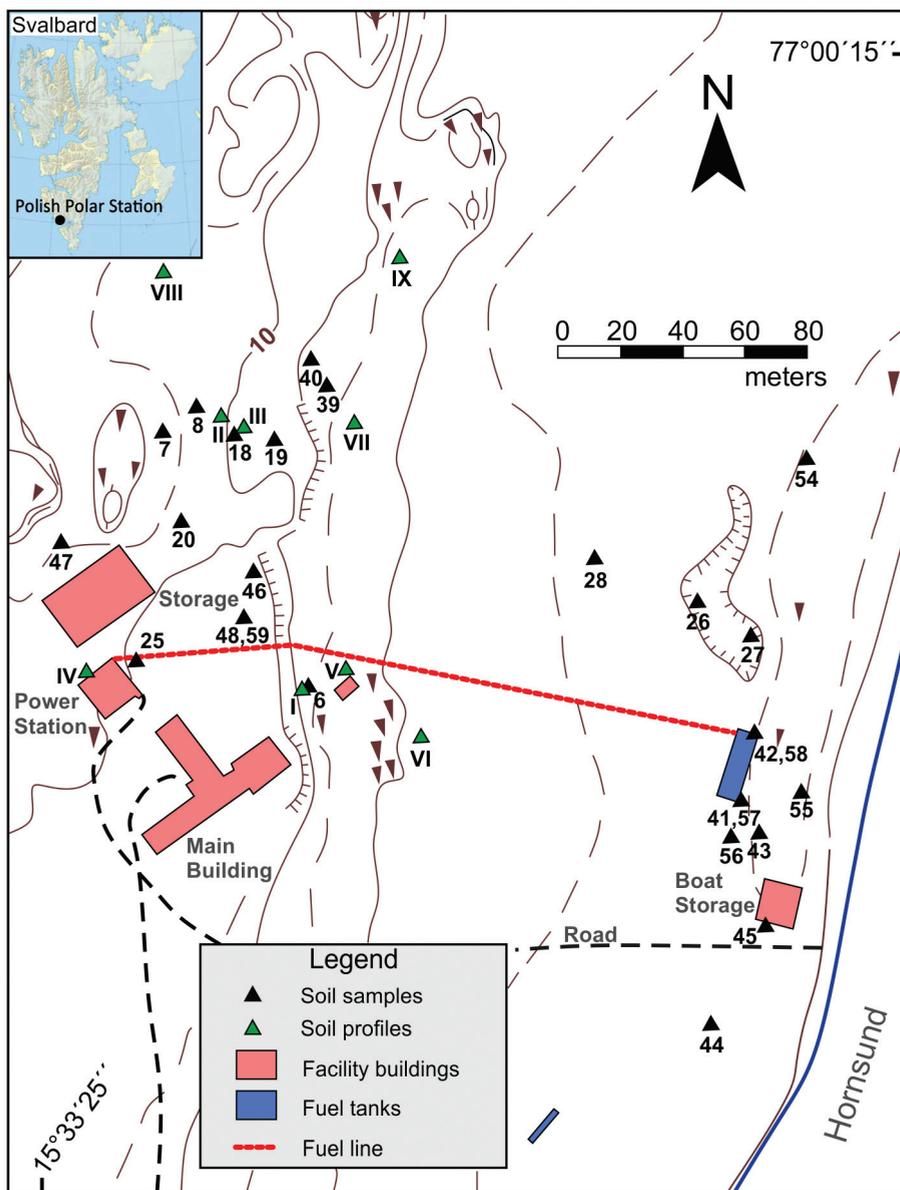


Fig. 1. Location of soil samples collected in 2012 in the vicinity of the Polish Polar Station. Map modified from Dąbrowski (1985).

Table 1

Concentration of Total Extractable Hydrocarbons (TEH) in soil samples collected in 2012 and concentration of n-Hexane Extractable Material (HEM) in soil samples collected in 1980 (Fig. 1).
Abbreviations: n.d., not detected; n.a., not analyzed.

Soil sample ID number	Soil profile ID number	Depth	Total Extractable Hydrocarbons TEH 2012	n-Hexane Extractable material HEM 1980
2012	2012	cm	mg·kg ⁻¹	mg·kg ⁻¹
1	I	0–2	4200	242370
2		2–5	500	770
3		5–15	190	3950
4		15–30	38	n.d.
5		30–50	29	1520
6		0–2	420	730
7		0–2	1600	1130
8		0–2	3200	44160
9	II	0–2	4500	8220
10		2–5	3800	9050
11		5–10	4900	1110
12		10–20	2300	n.d.
13		20–30	2500	n.d.
14	III	0–2	1500	55540
15		2–5	3400	n.d.
16		5–10	4000	n.d.
17		10–20	5500	n.a.
18		0–2	2200	9600
19		0–2	2600	n.a.
20		0–2	510	432520
21	IV	0–2	860	24530
22		2–5	640	31350
23		5–10	59	17650
24		10–20	n.d.	6210

Table 1 continued

Soil sample ID number	Soil profile ID number	Depth	Total Extractable Hydrocarbons TEH 2012	n-Hexane Extractable material HEM 1980
2012	2012	cm	mg·kg ⁻¹	mg·kg ⁻¹
25		0–2	1600	2140
26		0–2	n.d.	965
27		0–2	n.d.	2430
28		0–2	n.d.	1670
29	V	0–2	480	170010
30		2–5	500	42250
31		5–10	140	2900
32		10–20	47	1570
33		20–30	n.d.	1700
34	VI	0–2	31	23320
35		2–5	n.d.	2160
36	VII	0–2	n.d.	6100
37		2–5	31	2160
38		5–10	n.d.	n.d.
39		0–2	58	6310
40		0–2	n.d.	1830
41		0–2	4400	n.a.
42		0–2	500	n.a.
43		0–2	2600	n.a.
44		0–2	11000	n.a.
45		0–2	140	783
46		0–2	3200	n.a.
47		0–2	5000	n.a.
48		0–2	3200	n.a.
49	VIII	0–2	40	n.a.
50		2–5	27	n.a.

Table 1 continued

Soil sample ID number	Soil profile ID number	Depth	Total Extractable Hydrocarbons TEH 2012	n-Hexane Extractable material HEM 1980
2012	2012	cm	mg·kg ⁻¹	mg·kg ⁻¹
51	IX	0–2	25	n.a.
52		2–5	n.d.	n.a.
53		5–10	35	n.a.
54		0–2	33	n.a.
55		0–2	32	n.a.
56		0–2	120	n.a.
57		0–2	81	n.a.
58		0–2	30	n.a.
59		0–2	190	n.a.

for DRO (nC₁₀–nC₃₂) by gas chromatography according to EPA Method 8015C, Nonhalogenated organics by gas chromatography (US EPA 2007). Results indicated that the difference between concentrations of DRO representing TEH (naturally occurring compounds of polar fractions and non-polar hydrocarbons) and TPH of petroleum origin (non-polar hydrocarbons) were not significant in soil samples.

According to laboratory results, all method blanks, duplicates, laboratory spikes, and/or matrix spikes met quality assurance objectives. Identification and quantification of samples were based on comparisons of chromatographic data with reference standards. Values of TEH and HEM were expressed in mg·kg⁻¹ on a dry weight bases. Recoveries for TEH compounds varied between 61–93% and the lowest detection limit was 25 mg·kg⁻¹.

For soil samples collected in 1980, the content of petroleum-derived substances was determined by semi-microextraction (modified Soxlet extraction) with n-hexane (Hermanowicz *et al.* 1976), using a gravimetric method, which is less precise than gas chromatography that was used for 2012 samples. Also, as some crude oil and heavy oils may contain materials that are not soluble in n-hexane, recovery of these materials might have been low in soil samples from 1980 as compared to samples from 2012. Concentration of petroleum-derived substances in soil samples collected in 1980 is called n-Hexane Extractable Material (HEM). Soil samples from 1980 were not treated for the removal of naturally occurring hydrocarbons. Therefore, for the purpose of comparison, HEM

concentrations in soil samples from 1980 were compared with TEH concentration before silica gel cleanup in soil samples from 2012. The general name of “petroleum-derived fuel compounds” is used for HEM and TEH compounds.

Results

In 2012, soil samples were collected from areas with highest HEM concentrations found in 1980 (Krzyszowska 1986), which included the area of the main fuel barrel depot before removal of barrels in 2003 and 2004 (soil profiles No. II and III, samples No. 7, 8, 18, and 19), the area immediately below the upper sea terrace (soil profile No. VII, samples No. 39 and 40), the area below the smaller temporary fuel barrel storage area from the 1980's (soil profile No. I, V, VI, sample No. 6), the vicinity of the power station (soil profile No. IV, sample No. 25), and the vicinity of buildings (samples No. 20, 46, 47, 48, and 59) (Fig. 1). Additionally, soil samples were collected from the vicinity of the five fuel tank storage area located near the shoreline (samples No. 41, 42, 43, 44, 45, 55, 56, 57, and 58) and from a ground depression contaminated in 1980 (samples No. 26, 27, and 28) (Fig. 1). To establish the background level, control samples were collected away from sources of pollution (profiles No. VIII, IX and sample No. 54) (Fig. 1 and Table 1). It was necessary to estimate natural organic interference in contaminated soil. The content of TEH reached maximum of 40 mg·kg⁻¹ in control samples.

In the area of the 1980's main fuel barrel depot, concentrations of petroleum hydrocarbons in surface soil samples significantly decreased compared to samples collected 32 years earlier (*e.g.*, concentration decreased four, 14, and 37 times in samples No. 18, 8, and 14 respectively). A similar trend was observed in soil profile No. II, where concentrations of petroleum-derived fuel products decreased two fold at depths of 0–2 cm and three fold at depths of 2–5 cm after 32 years (Table 1). Only one surface soil sample (sample No. 7) contained higher concentrations of TEH as compared to 1980, which indicated possible additional pollution between 1980 and 2004 at this specific site. In general, surface soil samples from the 1980's main fuel barrel depot still contained TEH amounts that varied between 1500 mg·kg⁻¹ (profile No. III, sample No. 14) and 4500 mg·kg⁻¹ (profile No. II, sample No. 9), but these concentrations decreased between four and 37 times since 1980 (Fig. 1 and Table 1).

Concentrations of total petroleum hydrocarbons found on a flat area of the upper sea terrace increased with time below the ground surface (0–2 cm depth). Such increase was found in soil profiles No. II and III (Fig. 1). In soil profile No. II concentrations of TEH increased from undetectable at the depth of 10–30 cm in 1980 to 2300–2500 mg·kg⁻¹ in 2012 (Table 1). Also, in soil profile No. III, TEH in 2012 increased from undetectable below 2 cm in 1980

to 3400 mg·kg⁻¹, 4000 mg·kg⁻¹, and 5500 mg·kg⁻¹ at the depth of 5 cm, 10 cm, and 20 cm respectively (Table 1). Highest concentration of TEH was at the depth of 20 cm (5500 mg·kg⁻¹), which was approximately 3.5 times higher than at the depth of 0–2 cm (1500 mg·kg⁻¹) (Table 1). In the area of the 1980's main fuel barrel depot, concentrations of TEH significantly decreased in surface soil samples, but increased with depth after 32 years.

Areas below the escarpment where the main fuel barrel depot was located in 1980's did not show any contamination at any depth in 2012. Petroleum hydrocarbon concentrations decreased from 6100 mg·kg⁻¹ (0–2 cm depth) and 2160 mg·kg⁻¹ (2–5 cm depth) in 1980 to not being detected in 2012 (profile No. VII) (Fig. 1 and Table 1). Also, surface soil samples below the upper sea terrace did not show any contamination as compared to surface soil samples from 1980 (samples No. 39 and 40) (Fig. 1 and Table 1).

Another area where soil was collected to assess the range of contamination was an area below the smaller temporary fuel barrel storage from the 1980's (profiles No. I and V) (Fig. 1 and Table 1). TEH concentration on the escarpment surface decreased 58 times from 242370 mg·kg⁻¹ in 1980 to 4200 mg·kg⁻¹ in 2012 (sample No. 1; Table 1). In 2012, concentrations of TEH in deeper soil samples, below 15 cm depth, also decreased significantly and was comparable to control samples. In 2012, soil below the escarpment showed a significant decrease of TEH compared to samples from 1980 especially at shallower depths (decreases of 354 times from 170010 to 480 mg·kg⁻¹ at 0–2 cm depth and 84 times from 42250 to 500 mg·kg⁻¹ at 2–5 cm depth) (profile No. V; Table 1). Further along the ephemeral drainages, concentrations decreased from 23320 mg·kg⁻¹ at 0–2 cm to 31 mg·kg⁻¹ (profile No. VI) that is similar to the background soil (profile No. IX) (Table 1). The range of contamination from this source was significantly reduced along the drainage following slopes of the escarpment and was retained at the surface only to a distance of 20 m from sources of fuel spills existing in 1980.

Contamination in the vicinity of the power station and station's buildings was detected down to a 5 cm depth and decreased up to 48 times compared to 1980 samples (profile No. IV) (Fig. 1 and Table 1). Soil below 5 cm depth indicated similar concentrations of TEH as in control samples. Presently, an area utilized as a snow scooter storage contained a high concentration of TEH (3200 mg·kg⁻¹, sample No. 46) (Table 1). Other surface soil samples collected around buildings in 2012 contained TEH between 1600 mg·kg⁻¹ (sample No. 25) and 5000 mg·kg⁻¹ (sample No. 47) (Table 1). These contaminations were very localized and after this area had been graded and soil had been mixed by a grader blade the content of TEH decreased from 3200 mg·kg⁻¹ (sample No. 48) to 190 mg·kg⁻¹ (sample No. 59) (Table 1). In an area between the storage building and the 1980's main fuel barrel depot, concentrations of petroleum-derived fuel compounds from surface soil decreased approximately a few hundred times

from 432520 mg·kg⁻¹ to 510 mg·kg⁻¹ (sample No. 20) in 32 years (Table 1). Concentrations of TEH in surface soil of this area decreased due to soil being mixed and graded according to the station management practices.

Sediment samples collected in 2012 from a depression located near the beach did not show any contamination of petroleum derived components as was detected in 1980 (samples No. 26 and 27) (Fig. 1 and Table 1). Along the sea shore, another area of potential contamination included a motor boat storage area where sample No. 45 contained a higher concentration of TEH (140 mg·kg⁻¹) than control sample No. 54 (33 mg·kg⁻¹). However, this concentration was five times lower than in 1980 samples (Table 1).

An additional area being sampled in 2012 compared to 1980 is the current fuel storage tanks area near the harbor. A high concentration of TEH (4400 mg·kg⁻¹) was found in sediment under a valve of a pipeline at one of the fuel tanks (sample No. 41) (Fig. 1 and Table 1). The valve was used to check the fuel quality and was removed in 2011, eliminating the source of contamination. Another location with a high content of TEH was observed at areas where fueling of heavy equipment occurred. Here, concentrations of TEH reached between 500 mg·kg⁻¹ (sample No. 42) and 2600 mg·kg⁻¹ (sample No. 43) (Fig. 1 and Table 1). This area around fuel tanks is occasionally washed with surfactant removing petroleum hydrocarbons contaminants. Both areas listed above were washed with such solution and resampled. The content of TEH decreased from 4400 mg·kg⁻¹ (sample No. 41) to 81 mg·kg⁻¹ (sample No. 57) and from 500 mg·kg⁻¹ (sample No. 42) to 30 mg·kg⁻¹ (sample No. 58), which is similar to control sample No. 54 (Fig. 1 and Table 1).

An area between the motor boat storage and fuel tanks as well as an area south of the motor boat storage contained few spots (less than 0.5 m in diameter) with a higher content of TEH. These spots were easy to detect by the “oily” smell and shiny polish. Highest content of TEH was found in sediment sample No. 44 (11000 mg·kg⁻¹) with a lower concentration in sample No. 43 (2600 mg·kg⁻¹) (Fig. 1 and Table 1). These were very local and small areas of contamination that did not spread. For example, sample No. 55 located approximately 20 m from samples No. 43 and 41 (4400 mg·kg⁻¹) contained TEH similar to control samples (Fig. 1 and Table 1).

In summary, as of 2012, areas potentially contaminated with petroleum hydrocarbons covered 0.9 ha. This was a significant decrease compared to the approximate 1.8 ha contaminated in 1980 (Krzyszowska 1986). Extent of the 2012 contamination was limited to the immediate area of the 1980's main fuel barrel depot, areas below the smaller temporary fuel barrel storage area from the 1980's, vicinity of the power station and station's buildings, and an area near the fuel tanks on the beach near the harbor. Previously detected contamination in the area below the escarpment next to the main fuel barrel depot along the ephemeral drainages was not detected in 2012.

Discussion

The small scale of the area around the vicinity of polar stations with known fuel management practices provided an excellent case for monitoring of total petroleum hydrocarbons in soil after a fuel spill (Krzyszowska 1989). Changes of total petroleum hydrocarbon content with time created a unique research opportunity to analyze effects of fuel spills different than experimental spills of fuel in the Arctic (Walker *et al.* 1978; Bay 1997). Highest content of TPH in 2012 was detected at the beach where unloading of fuel occurs, around fuel tanks, within station buildings vicinities and in the 1980's main fuel barrel depot area. Currently, TPH concentrations in the vicinity of the Polish Polar Station are much lower than in 1980. Also, for example, they were at 20% of the level of the highest concentrations of TPH detected in four research facilities run by three nations in the Larsenann Hills in East Antarctica (Goldsworthy *et al.* 2003).

The largest decrease of TPH concentrations in soil collected in 2012 was found at the location of the main fuel barrels depot that was most contaminated area in 1980. Here, at surface sample No. 20 (Table 1), the highest concentration of petroleum hydrocarbons reached value of $432520 \text{ mg}\cdot\text{kg}^{-1}$ in 1980 (Krzyszowska 1986). A sample collected from a similar location in 2004–2005 (Luks 2005) contained $7013 \text{ mg}\cdot\text{kg}^{-1}$ petroleum hydrocarbons, while in 2012 the TEH content decreased to $510 \text{ mg}\cdot\text{kg}^{-1}$. Petroleum hydrocarbon concentrations decreased approximately to 2% of the original content within 24 years and to 0.1% after 32 years in surface soil. Such decrease in surface soils indicated that cumulative effect of biodegradation rate, volatilization, dispersion, and leaching of petroleum hydrocarbons in surface soil were important factors in decreasing their concentration in the active layer after local fuel spills in the 1980's.

At the ground surface, petroleum hydrocarbons were washed away along ephemeral drainages after spring meltdown on sloping areas. The largest decreases between samples collected in 1980's and 2012 were observed on slopes of an escarpment (sample No. 1) and along ephemeral drainages (sample No. 29) (Table 1) showing that surface water was the most important factor in petroleum hydrocarbons distribution. This is similar to findings at Ny-Ålesund area in Svalbard (Krzyszowska Waitkus 1997) and others in Alaska (Linkins *et al.* 1984; Barnes and Filler 2003).

Petroleum products penetrated from the surface by infiltrating deeper into soil on flat areas without vegetation cover. Over 32 years, concentrations of TEH increased from being not detected in 1980 below 2 cm depth to 3400, 4000, and $5500 \text{ mg}\cdot\text{kg}^{-1}$ at depths of 5, 10 and 20 cm respectively (profile No. III; Table 1). This was possible due to high infiltration rates of sandy soil at the range from 3×10^{-4} to $3\times 10^{-2} \text{ cm}\cdot\text{s}^{-1}$ (Krzyszowska 1981). Infiltrating petroleum products can move downward through unsaturated soil toward the water table

or the upper frost level, especially in sandy and dry soils (Sextone *et al.* 1978; Linkins *et al.* 1984; Filler *et al.* 2006; Barnes and Chuvilin 2009).

Fuel oils, due to their higher viscosity, tend to move horizontally (McGill *et al.* 1981), but as found in profile No. III, they also can penetrate deeper into soil profiles. Sediments at a 20 cm depth contained 3.6 times more petroleum hydrocarbons than at the surface (Table 1). These findings were also similar to research from Novosibirskie Island, where petroleum in upper horizons decreased by two–ten times in comparison with deeper soil levels (Kachinskii *et al.* 2014). Pathways of petroleum products once entering the soil are very dynamic and with time, the petroleum will migrate downward even in frozen soils as was found in other studies (Barnes and Filler 2003; McCarthy *et al.* 2004; Filler *et al.* 2006; Barnes and Wolfe 2008; White *et al.* 2008).

Petroleum hydrocarbons were still present in soils contaminated by local spillage 32 years earlier. Some studies performed in Alaska confirmed the presence of petroleum hydrocarbons in soil after refined oil spillage of 28 years (Sextone *et al.* 1978) and 15 years (Collins *et al.* 1993). Results of the study performed around the Polish Polar Station obtained a dissipation rate of TPH in soil profiles after 32 years from the spill. Concentrations of total petroleum hydrocarbons in surface soils of the unsaturated active layer above the permafrost decreased significantly mostly due to surface runoff and dispersion through ephemeral drainages. Concentrations of total petroleum hydrocarbons increased with depth after 32 years in sandy soils on a flat area of the upper sea terrace where 1980's main fuel barrel depot was located.

Station's management practices reducing concentrations of TPH in soil after the local spills, by applying surfactant and grading soil, follow the general trend of adding fertilizers and aerating of contaminated soil in polar conditions (Poland *et al.* 2003; Aislabie *et al.* 2006; Yang *et al.* 2009; AMAP 2010; Camenzuli and Freidman 2015). There are no specific soil quality standards for petroleum contamination in Svalbard. The Norwegian standard for light and heavy extractable petroleum hydrocarbons range is 100 mg·kg⁻¹ (Snape *et al.* 2008). Therefore, TEH contaminated areas above the background level of 40 mg·kg⁻¹ in 2012 was determined to cover 0.9 ha around the vicinity of the Polish Polar Station.

Acknowledgements. — The authors would like to thank anonymous reviewers for constructive advice that helped to improve the manuscript. The project was made possible through funding from the Institute of Ecology, Polish Academy of Science in 1980 and from the Svalbard Environmental Protection Fund, Project No. 12/09 in 2012 (RiS-ID 5480).

References

- AISLABIE J., SAUL D.J. and FOGHT J.M. 2006. Bioremediation of hydrocarbon-contaminated polar soils. *Extremophiles* 10: 171–179.
- AMAP 2010. *Assessment 2007: Oil and gas activities in the Arctic – effects and potential effects. Volume 2.* Arctic Monitoring and Assessment Programme (AMAP), Oslo: vii+277 pp.
- ATLAS R.M. 1986. Fate of petroleum pollutants in Arctic ecosystems. *Water Science Technology* 18: 59–67.
- BARNES D.L. and FILLER D.M. 2003. Spill evaluation of petroleum products in freezing ground. *Polar Record* 39: 385–390.
- BARNES D.L. and WOLFE S.M. 2008. Influence of ice on the infiltration of petroleum into frozen coarse-grained soil. *Petroleum Science and Technology* 26: 856–867.
- BARNES D.L. and CHUVILIN E. 2009. Migration of petroleum in permafrost-affected regions. In: R. Margesin (ed.) *Permafrost Soils, Soil Biology 16*. Springer-Verlag, Berlin, Heidelberg: 263–278.
- BAY C. 1997. *Effects of experimental spills of crude and diesel oil on Arctic vegetation. A long-term study on high Arctic terrestrial plant communities in Jameson Land, central East Greenland.* [Danish] Ministry of Environment and Energy, National Environmental Research Institute Technical Report 205, Roskilde: 44 pp.
- BIRKENMAJER K. 1960. Course of the geological investigations of the Hornsund area, Vestspitsbergen, in 1957–1958. *Studia Geologica Polonica* 11: 7–34.
- BØRRESEN M., BREEDVELD G.D. and RIKE A.G. 2003. Assessment of the biodegradation potential of hydrocarbons in contaminated soil from a permafrost site. *Cold Regions Science and Technology* 37: 137–149.
- CAMENZULI D. and FREIDMAN B.L. 2015. On-site and in situ remediation technologies applicable to petroleum hydrocarbon contaminated sites in the Antarctic and Arctic. *Polar Research* 34, 24492.
- COLLINS C.M., RACINE C.H. and WALSH M.E. 1993. *Fate and effects of crude oil spilled on Subarctic permafrost terrain in interior Alaska. Fifteen years later.* US Army Corps of Engineers Cold Regions Research & Engineering Laboratory Report 93-13, Hanover: 20 pp.
- DĄBROWSKI S. 1985. Spitsbergen, Polish Polar Station in Hornsund. Maps in the scale of 1:5000 and 1:500. *Polish Polar Research* 6: 577–582 (+ two maps).
- ERIKSSON M., KA J.-O. and MOHN W.W. 2001. Effects of low temperature and freeze-thaw cycles on hydrocarbon biodegradation in Arctic tundra soil. *Applied and Environmental Microbiology* 67: 5107–5112.
- EVERETT K.R. 1978. Some effects of oil on the physical and chemical characteristics of wet tundra soils. *Arctic* 31: 260–276.
- FILLER D.M., KENNICUT II M.C., SNAPE I., SWEET S.T. and KLEIN A.G. 2015. Arctic and Antarctic spills. In: M. Fingas (ed.) *Handbook of oil spill science and technology*. John Wiley & Sons, Inc., Hoboken: 497–512.
- FILLER D.M., REYNOLDS C.M., SNAPE I., DAUGULIS A.J., BARNES D.L. and WILLIAMS P.J. 2006. Advances in engineered remediation for use in the Arctic and Antarctica. *Polar Record* 42: 111–120.
- GOLDSWORTHY P.M., CANNING E.A. and RIDDLE M.J. 2003. Soil and water contamination in the Larsenann Hills, East Antarctica. *Polar Record* 39: 319–337.
- HERMANOWICZ W., DOŻAŃSKA W., DOJLIDO J. and KOZIOROWSKI B. 1976. *Methods for physical and chemical analysis of water and sewage*. Arkady, Warszawa: 845 pp. (in Polish).

- KACHINSKII V.L., ZAVGORODNYAYA Y.A. and GENNADIEV A.N. 2014. Hydrocarbon Contamination of Arctic Tundra Soils of the Bol'shoi Lyakhovskii Island (the Novosibirskie Islands). *Eurasian Soil Science* 47: 57–69.
- KRZYSZOWSKA A. 1981. The degree of tundra degradation in the surroundings of the Hornsund Polar Station (Spitsbergen) – reaction of the environment to human impact. *Polish Polar Research* 2: 73–86.
- KRZYSZOWSKA A. 1985. Tundra degradation in the vicinity of the Polish Polar Station, Hornsund, Svalbard. *Polar Research* 3: 247–252.
- KRZYSZOWSKA A. 1986. The balance of materials, waste, and energy of the Polish Polar Station (Hornsund, Svalbard) and the station's effect on its immediate surroundings. *Ekologia Polska* 34: 227–246.
- KRZYSZOWSKA A. 1989. Human impact on tundra environment at the Ny-Ålesund Station, Svalbard. *Polar Research* 7: 119–131.
- KRZYSZOWSKA A. 1990. The content of fuel oil in soil and effect of sewage on water nearby the H. Arctowski Polish Antarctic Station (King George Island). *Polskie Archiwum Hydrobiologii* 3: 311–324.
- KRZYSZOWSKA A. 1993. Human impact around Polar Stations on Fildes Peninsula (King George Island, Antarctica). *Proceedings XX Polar Symposium, Man impact on polar environment*, Lublin: 203–208.
- KRZYSZOWSKA WAITKUS A. 1997. *The Effect of Oil Spills and Traffic in the Vicinity of Ny-Ålesund, Svalbard*. Unpublished Environmental Impact Assessment (EIA) technical report [results also cited in EIA98, *i.e.*, Sears *et al.* 1998]. University of Wyoming, Laramie: 57 pp.
- LINKINS A.E., JOHNSON L.A., EVERETT K.R. and ATLAS R.M. 1984. Oil spills: Damage and recovery in tundra and taiga. In: J. Cairns Jr and A.L. Buikema Jr. (eds) *Restoration of habitats impacted by oil spills*. Butterworth Publishers, Massachusetts: 135–155.
- LUKS B. 2005. Wpływ Polskiej Stacji Polarnej w Hornsundzie na zanieczyszczenie i degradację pokryw glebowej. *Praca magisterska. Wydział Geografii i Studiów Regionalnych Uniwersytetu Warszawskiego*, Warszawa: 73 pp. (in Polish).
- MARGESIN R. and SCHINNER F. 2001. Biodegradation and bioremediation of hydrocarbons in extreme environments. *Applied Microbiology and Biotechnology* 56: 650–663.
- MCCARTHY K., WALKER L. and VIGOREN L. 2004. Subsurface fate of spilled petroleum hydrocarbons in continuous permafrost. *Cold Region Science and Technology* 38: 43–54.
- MCGILL W.B., ROWELL M.J. and WESTLAKE D.W.S. 1981. Biochemistry, ecology, and microbiology of petroleum components in soil. In: E.A. Paul and J.N. Ladd (eds) *Soil biochemistry*. Marcel Dekker, New York: 229–296.
- POLAND J.S., RIDDLE M.J. and ZEEB B.A. 2003. Contaminants in the Arctic and the Antarctic: a comparison of sources, impacts, and remediation options. *Polar Record* 39: 369–383.
- RIKE A.G., HAUGEN K.B., BØRRESEN M., ENGENE B. and KOLSTAD P. 2003. In situ biodegradation of petroleum hydrocarbons in frozen arctic soils. *Cold Regions Science and Technology* 37: 97–120.
- RIKE A.G., SCHIEWER S. and FILLER D.M. 2008. Temperature effects on biodegradation of petroleum contaminants in cold soils. In: Filler D.M., I. Snape and D.L. Barnes (eds) *Bioremediation of petroleum hydrocarbons in cold regions*. Cambridge University Press, Cambridge: 84–108.
- SEXTONE A., EVERETT K., JENKINS T. and ATLAS R.M. 1978. Fate of crude and refined oils in North Slope soils. *Arctic* 31: 339–347.
- SHEARS J., THEISEN F., BJØRDAL A., and NORRIS S. 1998. *Environmental impact assessment Ny-Ålesund international scientific research and monitoring station, Svalbard*. Norsk Polarinstitut Meddelelser No. 157, Tromsø: 56 pp.

- SNAPE I., ACOMB L., BARNER D.L., BAINBRIDGE S., ENO R., FILLER D.M., PLATO N., POLAND J.S., RAYMOND T.C., RAYNER J.L., RIDDLE M.J., RIKE A.G., RUTTER A., SCHAFER A.N., SICILIANO S.D. and WALWORTH J.L. 2008. Contamination, regulation, and remediation: an introduction to bioremediation of petroleum hydrocarbons in cold regions. *In*: D.M. Filler, I. Snape and D.L. Barnes (eds) *Bioremediation of petroleum hydrocarbons in cold regions*. Cambridge University Press, Cambridge: 1–37.
- US EPA 2007. *Test Methods for Evaluating Solid Waste: Physical/Chemical Methods*. U.S. Environmental Protection Agency (EPA) Publication SW-846, Third Edition, Final Update III-A. US EPA Federal Registry.
- WALKER D.A., WEBBER P.J., EVERETT K.R. and BROWN J. 1978. Effects of crude and diesel oil spills on plant communities at Prudhoe Bay, Alaska and the derivation of oil spill sensitivity maps. *Arctic* 3: 242–259.
- WHITE D.M., GARLAND S. and WOOLARD C.R. 2008. Analytical methods for petroleum in cold region soils. *In*: D.M. Filler, I. Snape and D.L. Barnes (eds) *Bioremediation of petroleum hydrocarbons in cold regions*. Cambridge University Press, Cambridge: 109–124.
- YANG S.Z., JIN H.J., WEI Z., HE R.X., JI Y.J., LI X.M. and YU S.P. 2009. Bioremediation of oil spills in cold environments: A review. *Pedosphere* 19: 371–381.
- ZIAJA W. and SKIBA S. 2002. *Sørkappland landscape structure and functioning (Spitsbergen, Svalbard)*. Wydawnictwo Uniwersytetu Jagiellońskiego, Kraków: 119 pp.

Received 8 April 2019

Accepted 23 September 2019