Performance of five drilling waste sumps, Mackenzie Delta, western Arctic Canada

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Abstract

Petroleum resource exploration and development has occurred in the Northwest Territories since the 1920s. Freezing-point depressants, mainly potassium chloride, were added to drilling fluids in many wells to maintain circulation and the thermal integrity of permafrost penetrated during drilling. Disposal of these fluids was generally in large pits, or sumps, excavated in permafrost, with the intention that frozen ground would contain the fluids indefinitely. Climatic warming in northwest Canada has raised the temperature of near-surface permafrost, increasing the potential for failure of over 220 sumps constructed in the region. Electro-magnetic surveys were conducted with an EM-31 to determine the ground conductivity fields on and off sumps at three locations in the outer Mackenzie Delta. The surveys were complemented by investigations of water conductivity in ponds also on and off the sump caps. Two of the sumps (C-42 and B-19) were low-lying and occasionally flooded, while the third (L-38) was at the coast and regularly inundated. Ground conductivities at these three sumps built in the 1970s were similar to undisturbed terrain. The most recent sump, 3/4/5 L-38 (2002), had high conductivity below its cap. An intermediate state was measured at 2 L-38, built in 1998, where the spatial concentration of ground conductivity has diminished since a survey in 2012. Both observations suggest the contents of the sumps are being lost. Enhanced conductivities in some ponds on sump caps imply the possible emergence of the sump fluids via these water bodies.

1 Introduction

The Mackenzie Delta is a region of significant discovered and predicted hydrocarbon (oil and gas) resources (French 1980). In the 1970s and 1980s, 16 companies drilled 230 onshore wells to prospect and delineate these reserves (Simpson and van Gulck 2020). The projects required drilling fluids with freezing points below the temperature of permafrost, as the wells would typically extend to depths around 2500 m, thereby penetrating perennially frozen ground (Shell Canada Ltd 2005).

Drilling fluids were necessary to clean the drill bits, reduce friction, and provide borehole stability (French 1980). Freezing point depressants, primarily potassium chloride (KCl), were added with other substances, such as bentonite, cellulose polymers, lignosulphonates, and sodium hydroxide, to influence the chemical and physical properties of the fluids so that they might perform well at temperatures below 0 °C (Hrudey 1979). The fluids were recycled and reused several times during each project before being discarded (Hrudey 1979). KCl in these fluids allows them to be traced in the environment, as background concentrations of KCl are low in comparison with drilling fluids (Dyke 2001).

The fluids, or drilling muds, were disposed of in pits, or sumps, blasted and dug in permafrost (French 1980). The sumps were large enough to accommodate between 0.78 and 1.3 m^3 of drilling mud for every meter of hole drilled (Hardy and Stanley 1988). The muds were sometimes frozen in the sumps before being covered with excavated ground materials to create a domed cap (Hardy and Stanley 1988). The sump caps were approximately 5 m thick and sufficient to contain the active layer (Figure 1). Permafrost then aggraded into the sumps, freezing the fluids in place for permanent disposal.

The basis for development of sumps as disposal sites was the expectation that ice-bonded permafrost would be an effective, impermeable, and permanent containment medium. This position must now be reassessed. First, snow accumulation on the sides of sumps and in vegetation that developed on sump caps has led to increases in mean annual ground temperature and warming of sump materials (Kokelj et al. 2010). Second, salinities of disposed materials were elevated in part of the sump by solute expulsion during freeze back, lowering the freezing points of the solutions. Such volumes of elevated salt concentrations have been inferred by electromagnetic surveys (Dyke 2001). Third, rising permafrost temperatures due to climatic warming no longer ensure that the ground surrounding sumps will remain at a lower temperature than the freezing point of the drilling muds (Burn and Kokelj 2009). As a result, the ability of the sumps to contain these fluids is not assured.

The purpose of this paper is to investigate the stability of five sumps of similar characteristics in a low-lying, occasionally flooded deltaic environment (Figure 2). At each sump, data were collected on ground conductivity, active-layer depth, soil grain size, and ponding. These data were compared with surveys from 15–20 years ago to determine changes in conditions at the sumps, and to assess sump performance in containing the drilling wastes.

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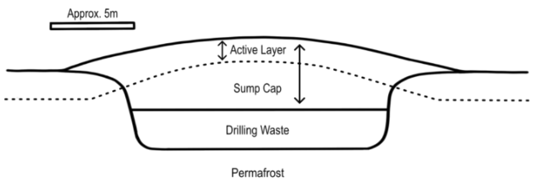

Figure 1. Cross-section of a sump with representative dimensions.

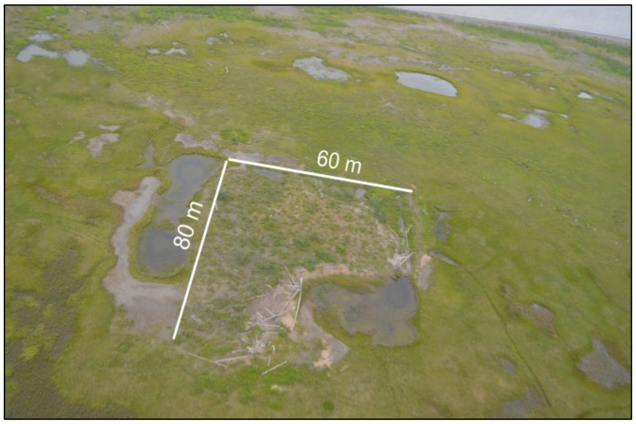

Figure 2. Aerial image of sump B-19 with dimensions indicated in meters.

2 STUDY AREA

The Mackenzie Delta is an alluvial plain 210 km in length and on average 62 km wide (Burn and Kokelj 2009). This dynamic environment has shifting channels and thousands of lakes at various stages of expansion, drainage, and infilling (Mackay 1963). The Mackenzie Delta receives about 128 Mt of sediment each year, with the vast majority supplied by Mackenzie River (Burn and Kokelj 2009). These sediments are dominantly fine sand and silts (Kokelj and Burn 2005). The five sumps studied are in the outer delta near the Beaufort Sea (Figure 3).

Vegetation distribution in the outer delta varies with gradients in soil moisture, topography, and nutrient conditions (Mackay 1963). In the alluvial plain, vegetation ranges from bare ground near the channel, through tall (1–3 m), medium (0.6–1 m), and low (0.4–0.6 m) willows, to a distil sedge wetland (Morse et al. 2012). On alluvial flats, sedges grow where it is muddy, but horsetails predominate at the outermost Delta (Mackay 1963). Snow cover in the region varies spatially. Tall vegetation traps up to 2 m of snow in some areas but vegetation-free terrain is windswept and has very shallow snow cover, typically less than 0.3 m (Kokelj et al. 2010).

Tuktoyaktuk, the closest weather station received a mean annual precipitation of 160 mm in 1981–2010 and an average annual snow depth of 103.1 cm (ECCC 2020). For the same period, the mean annual air temperature was -10.1 °C. Warming of the western Arctic has been faster than the global average; annual mean air temperatures have increased by up to 0.77 °C per decade since 1971; the magnitude of the warming in the Delta area has been up to 2.3 °C for 30-year mean temperatures and 3.7 °C in 10-year means for 1961–70 and 2011–20 (Burn and Kokelj 2009; Thienpont et al. 2013; Schetselaar et al. 2023).

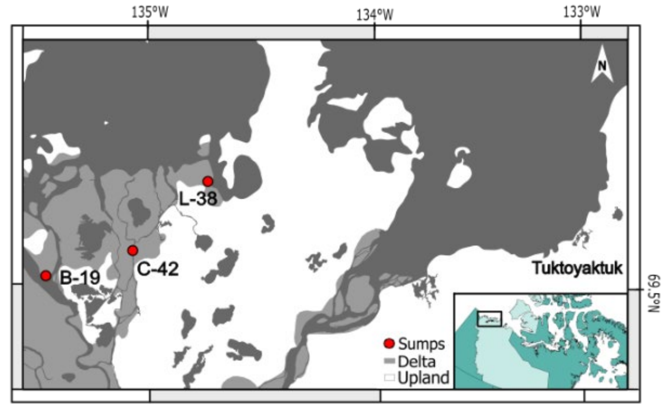

Figure 3. Study area including locations of sumps B-19, C-42, and L-38.

The outer Delta area is underlain by continuous permafrost. The area was subaerially exposed for much of Wisconsinan glaciation, allowing permafrost to develop up to 600 m (Taylor et al. 1996). Sea level rise since glaciation led to submergence of most of the area, but recently progradation of the Delta has caused the ground surface to emerge (Morse et al. 2012). Mean annual ground temperatures in undisturbed ground range from -3 to -5 °C at the top of permafrost (Burn and Kokelj 2009).

The active layer in alluvial terrain is deeper than in the adjacent well-drained uplands due to early removal of snow in the spring flood and the prevalence of wet soils. At alluvial locations with low-shrub tundra, active layers are 0.4–1.2 m thick (Morse et al. 2012; Duchesne et al. 2015). Snow drifts up to 2.5 m thick may accumulate on sump caps with tall shrubs, whereas caps vegetated with only sedges and grasses have a thin snow cover similar to undisturbed tundra (Kokelj et al. 2010).

3 MACKENZIE DELTA SUMPS

Guidelines for best practices of construction were established during the development of sumps in 1960–2005 (Spencer Environmental 1987). The ideal terrain for construction is flat or gently sloping with topographic highs that promote surface drainage. Sumps should be a minimum of 100 m from the ordinary high-water mark of any permanent water body or stream. These guidelines imply that proper site selection requires inspection of the proposed site for a comprehensive assessment of terrain, hydrologic, permafrost conditions, and land use prior to the development of the sump (Kokelj and GeoNorth 2002). Used drilling fluids should be stored below the permafrost table in the sump for disposal. Since active-layer depths in the Mackenzie Delta may exceed 1.2 m, the surface of the waste fluids should be at a depth of least 2 m (Kokelj and GeoNorth 2002).

4 FIELD LOCATIONS

4.1 Mallik L-38, 2 L-38 and 3/4/5 L-38 sumps

The Mallik site is in low-lying coastal terrain of the outer Mackenzie Delta and is the farthest north of the locations discussed in this paper (Figures 3, 4A). There were three distinct projects at the site (Table 1). The first well, L-38, was drilled by Imperial Oil in 1972. The second and third projects were joint undertakings of Japex and the Geological Survey of Canada in 1998 and 2002. Saline drilling fluids were used in each case (Piraux et al. 2016). The sumps built for these wells are near sea level and are inundated from time to time. The patchy vegetation consists mainly of graminoid species, such as sedges and cotton grasses, with a few sporadic low shrubs and mosses. Sump 3/4/5 L-38 was not seeded after construction and much of the deltaic silt cap remains unvegetated (Piraux et al. 2016). Temperature measurements at 1.5 m below the sump cap have indicated that the material had an annual mean temperature of -7.8 °C in 2007–2013 (Piraux et al. 2016).

4.2 Taglu C-42

C-42 (dimensions in Table 1) is near Harry Channel of the Mackenzie Delta, approximately 140 m from the riverbank (Figure 3). This sump was also constructed in 1972 by Imperial Oil. A combination of non-aqueous drilling fluids and aqueous muds with freezing-point depressants was used for the well (Imperial Oil Resources Ltd 2004). Vegetation has colonized the cap of the sump and surrounding edges of the structure. Willows, 1–2.5 m tall, sedges and alder bushes are present throughout the disturbed area. The sump is surrounded by undisturbed, low-lying, saturated tundra. There are large ponds on and directly adjacent to the sump cap (Figure 4B).

4.2 Niglintgak B-19

B-19 (dimensions in Table 1) is 180 m from Middle Channel of the Mackenzie Delta (Figures 2 and 3). The sump was constructed in 1976 by Shell Canada and is surrounded by wooden pilings that were used to support infrastructure during drilling (Figure 4C). Aqueous KCl polymer drilling fluids were used in well development (Shell Canada Ltd 2005). Vegetation adjacent to the sump is dominated by sedges and cotton grasses in the annually flooded terrain. Stranded driftwood is scattered throughout the site. The sump cap supports a few willows, 1–2 m tall, in addition to patches of unvegetated ground.

5 FIELD METHODS

KCl and other salt solutions are electrically conductive and can be traced in the ground with electromagnetic (EM) induction techniques. Surveys of the sumps were conducted in August and September 2022 with a Geonics EM-31 instrument. The EM-31 induces an electromagnetic field in the ground and, with vertical dipole orientation, has penetration of approximately 5 m (McNeill 1980; Figure 5).

Table 1. Dimensions in meters of Mallik sumps as indicated in Piraux et al. (2016). C-42 and B-19 were measured (in meters) using Google Earth.

Sump	Width	Length	Depth
L-38	46	55	3.5
2L-38	35	45	3.5
3/4/5 L-38	85	100	2
C-42	50	60	N/A
B-19	60	80	N/A

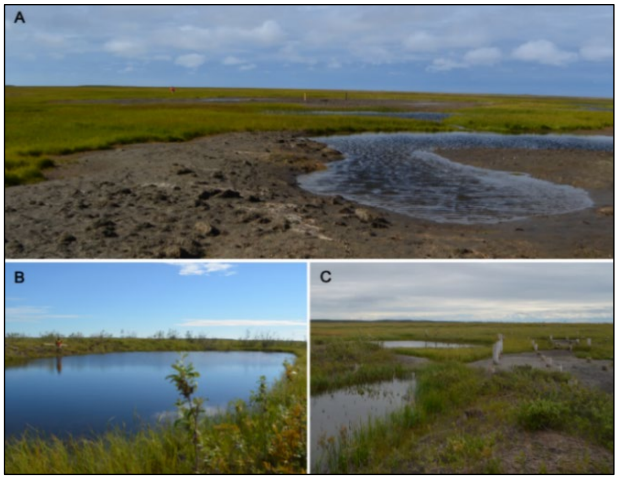

Figure 4. Ground level view of: (A) 3/4/5 L-38 looking northeast; (B) C-42 west sump cap pond; (C) B-19 sump cap facing southwest towards the abandoned pilings.

The EM-31 survey began at the centre of the sump cap and extended 100 m in all cardinal directions into undisturbed terrain (Figure 6). Concentric circles were surveyed at 10 m intervals to fill out the area. The survey was carried out around the perimeters of large ponds.

Grain size analysis was conducted by the pipette method on samples from each sump cap and undisturbed terrain 100 m from the sump. The samples were collected from 40–60 cm depth with a probe sampler. A cylindrical sample 2 cm in diameter and 20 cm long was extracted from 24 locations at each site. Four samples were collected from the sump cap and the others were collected at 20 m intervals from the sump centre along 100 m lines extending outwards in each cardinal direction. Thaw depths were obtained by probing.

Photographs were taken from the air in 2022 at each site. General characteristics of the site including the percentage of sump cap that was covered by ponds were calculated in ArcGIS Pro from these images. The conductivity of pond water was obtained with a YSI Pro 1030 conductivity meter in the lab.

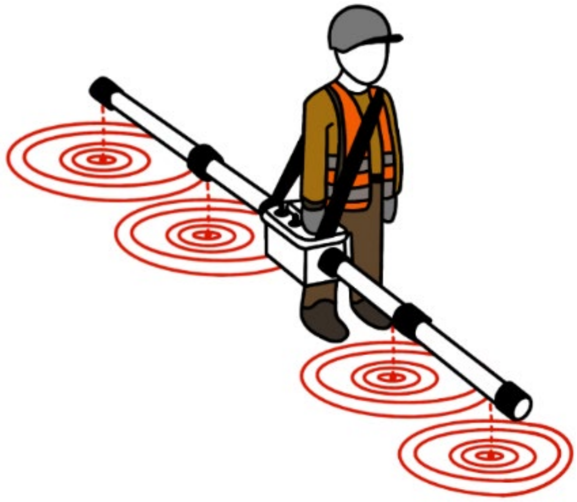

Figure 5. Diagrammatic sketch of EM-31 instrument assembled to conduct a field survey.

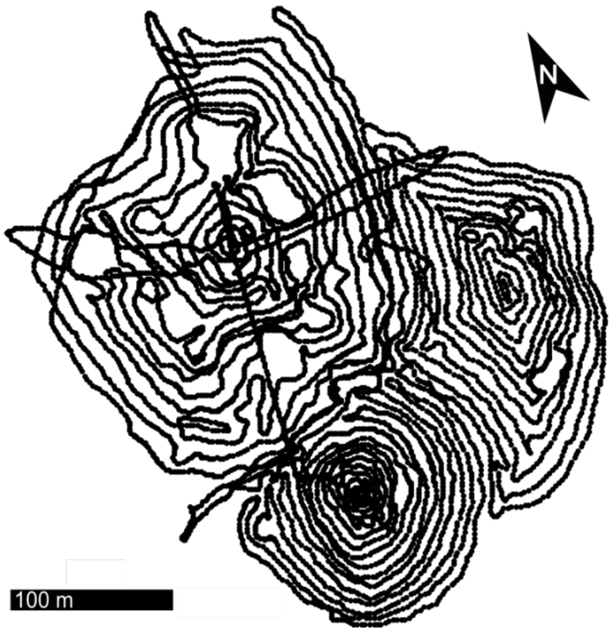

Figure 6. Path of EM-31 survey at the Mallik site.

6 Results

6.1 Grain-size composition

Grain-size composition at all three locations was similar on the sump cap and in undisturbed terrain (Table 2). The dominant grain size was silt, comprising 60–70%. This is expected as the deltaic sediments of the Mackenzie River are composed primarily of fine-grained sediments. 3/4/5 L-38 had the highest sand-sized fraction at ~30%, whereas this was less than 20% for both C-42 and B-19.

Table 2. Grain-size composition on sump cap and in undisturbed terrain.

Sump	Location	% Sand	% Silt	% Clay
3/4/5 L-38	Cap	29	60	11
	Undisturbed	28	69	3
C-42	Cap	18	67	15
	Undisturbed	16	71	13
B-19	Cap	17	68	16
	Undisturbed	17	70	13

6.2 Thaw depths on and near sumps

Thaw depths at 3/4/5 L-38 and C-42 were deepest on the sump cap (Table 3). The thawed ground at B-19 was thickest on the sides of the sump. Relatively little difference was measured between thaw depths on and off the sump caps. Piraux et al. (2016) reported thaw depths in early September 2012 for 2 L-38 and 3/4/5 L-38. Depth on sump caps was recorded at 140 cm and 132 cm respectively, and 136 cm and 131 cm in the perimeter (Piraux et al. 2016).

Table 3. Average thaw depths ($\bar{X}$, cm) on and adjacent to sumps, mid-August 2022, and sample size (n).

	Cap		Sides		Undisturbed	
Sump	$\bar{X}$	n	$\bar{X}$	n	$\bar{X}$	n
3/4/5 L-38	111	2	98	8	100	8
C-42	90	2	81	2	61	9
B-19	80	1	96	8	82	3

6.3 Sump ponding

In 2022, ponds were estimated to cover 8% of the L-38 sump cap, 16% of the 2 L-38 cap, 12% at 3/4/5 L-38, 35% at C-42, and 13% at B-19. Figure 7 presents three images of sump 3/4/5 L-38 taken at 10-year intervals. Development of ponds between 2002 and 2012 is evident, but little change is observed from 2012–2022.

The thermal influence of ponds promotes thickening of the active layer and degradation of the subjacent permafrost. In the outer Mackenzie Delta area, pond water more than 1.5–2 m deep is unlikely to freeze in winter (Burn 2002). Ponds of sufficient depth are likely a route for diffusion of saline pore fluids from within the sump to the surface. No pond depths were measured in this study.

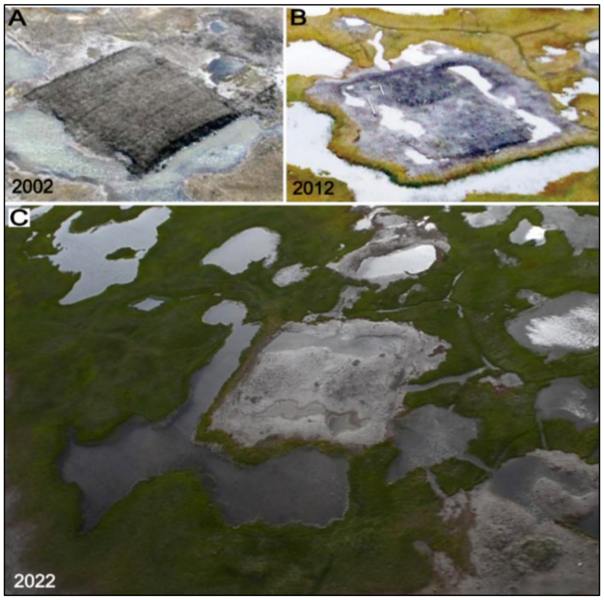

Figure 7. Development of ponds on the sump cap and surrounding terrain at 3/4/5 L-38, as recorded by aerial photographs from (A) 2002; (B) 2012; (C) 2022.

6.4 Pond Water Conductivity

Table 4 presents electrical conductivity of water from ponds on sump caps and in undisturbed ground nearby. Conductivities were highest at Mallik because of proximity to the ocean and inundation at high tide or during storm surges. Nevertheless, ponds on the two oldest sump caps at the site, L-38 and 2 L-38, had higher conductivity water than in undisturbed ground, or on the youngest sump.

At C-42, water collected from the sump cap had lower conductivity than from undisturbed ground nearby. The conductivity in these ponds declined as distance between the pond and the sump increased (Table 4). Ponds on B-19 had a conductivity higher than water from undisturbed ground at C-42, the nearest site to B-19 with samples from off the cap.

6.5 Ground conductivity surveys

EM-31 surveys were conducted in 2022 at all sumps, including the three sumps at the Mallik site (Figures 6 and 8). Records from a survey in 1998 are available for Niglintgak B-19 (Dyke 2001) and for 2012 at Mallik (Figures 8 and 9). Figure 8 presents maps of conductivity at the Mallik site. All three sumps were included in the 2022 survey (Figure 8B).

The conductivity peak evident in Figure 8A east of sump 3/4/5 also diminished in 2022, so sump 2 L-38 is not now as easily distinguished. Conductivity measurements from all three Mallik sumps and from undisturbed ground at the site are presented as box-and-whisker plots in Figure 10A. The Mallik site has relatively high values of ground conductivity because of its coastal location and susceptibility to inundation by sea water, as shown by the pond water conductivity measurements (Table 4). Figure 10A indicates the mean conductivity measured at the

Table 4. Conductivity of pond water on and adjacent to sumps (mS/m). For comparison with ground conductivity.

Sump	Location	Conductivity (mS/m)
L-38	10 m South West	127.6
	West side sump cap	151.4
2L-38	West side sump cap	147.2
3/4/5 L-38	South East sump cap	128.3
	60 m South	126.8
C-42	West sump cap	30.2
	20 m East	65.9
	40 m South	47.4
	60 m North	29.4
B-19	North side of sump cap	88.3
	South side of sump cap	75.0
Mackenzie Delta Water		30
Ocean Water		5500
Deionized Water		17.3

sumps systematically declines with time, so that in 2022, the conductivities measured at the oldest sump, L-38, are comparable to values from undisturbed terrain in the survey area. The highest measurements made at the site were within the boundaries of sump 3/4/5 L-38, but data collected from 2 L-38 were of lower conductivity than in some parts of the undisturbed coastal terrain. The presence of many outliers in undisturbed terrain at the Mallik site (Figure 10A) is due to the zone of elevated ground conductivity, where the site is flooded by Beaufort Sea water.

Figure 9 presents surveys at B-19 in 1998 and 2022. In 1998 the focus of the conductivity distribution coincides with the location of a sump-cap pond in 2022, even though the 1998 survey was conducted in April, under late winter conditions. There is a small anomaly in the northeast corner, also the location of a pond in 2022. Figure 10B presents box-and-whisker plots of ground conductivity at the site on and off the sump cap. The distributions of measurements are comparable between these two areas (cap and undisturbed).

Figure 10B also presents data collected at Taglu C-42. The distribution of conductivities shows higher values over the sump cap than in undisturbed terrain, but the population is of lower conductivity overall than at B-19.

These data are reflected in the pond-water conductivities presented in Table 4, which were also higher at B-19 than C-42.

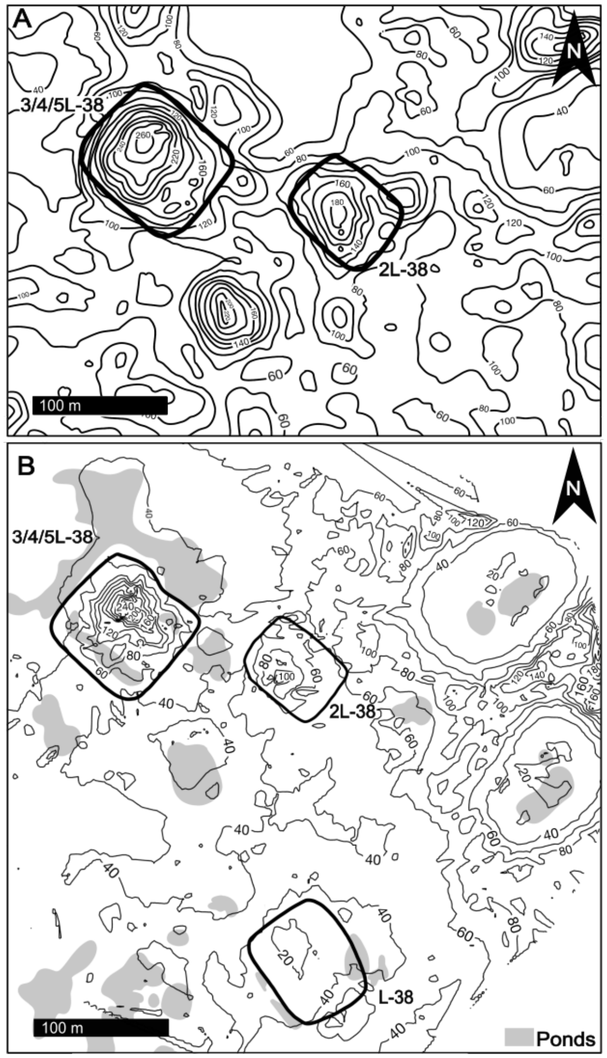

Figure 8. Maps of ground conductivity; (A) 2012 (modified from Piraux et al. 2016) and (B) 2022 surveys. Sumps are outlined in a thick black line on each diagram. The contour interval is 20 mS/m.

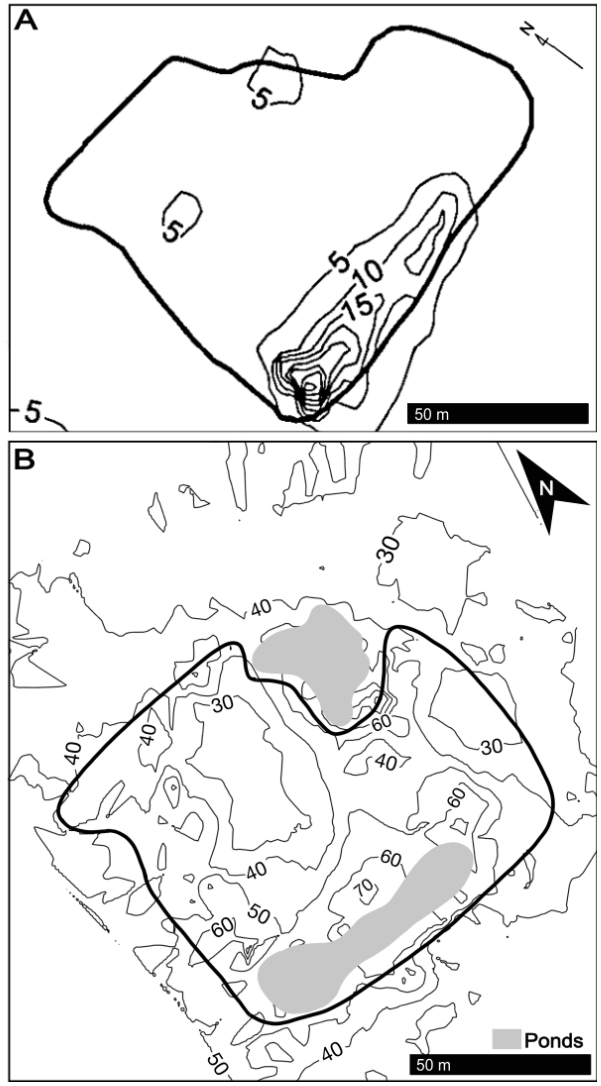

Figure 9. B-19; (A) in 1998 (modified from Dyke 2001) and (B) in 2022 surveys. The sump is outlined with a thick black line on each map. Contour lines are at intervals of (A) 5 mS/m and (B) 10 mS/m.

7 DISCUSSION

7.1 Grain-size composition and thaw depth

Soil physical properties on and off the sumps appear to be similar. The grain-size determinations indicate the similarity of sediment characteristics both on and off the sump caps and within the region (Table 1). The samples collected from the sump caps indicate that the material was locally sourced. The sumps are not covered by a sand or gravel cap, and therefore these materials will have considerable unfrozen water content at temperatures below 0 °C (Williams and Smith 1989).

No systematic differences in thaw depths were observed in these data between undisturbed terrain, sump sides, and sump cap (Table 3). The greatest thaw depths at each site were measured on the sump cap or sides, not in undisturbed terrain, but the differences were small in absolute terms.

7.2 Ground conductivity

Figure 10 indicates the distribution of conductivity measurements made on the sumps and in undisturbed ground nearby. The measurements on the caps of B-19, C-42, and L-38 were of similar value and consistent with data from undisturbed ground. These sumps were built in the 1970s. Data from the cap of 2 L-38 were elevated above the values from the older sumps, and data from 3/4/5 L-38 were the highest recorded from sump caps. The conductivities measured at 2 L-38 appeared spatially less pronounced in the survey of 2022 than in 2012.

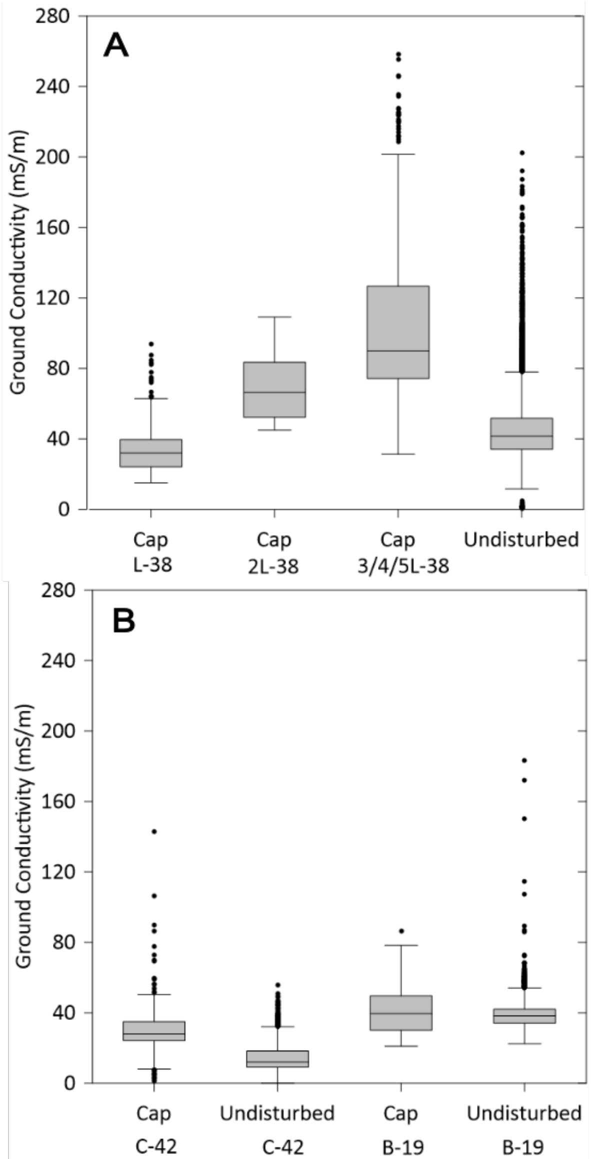

Figure 10. Distribution of ground electrical conductivity measurements between sump caps and undisturbed terrain (in mS/m) at (A) Mallik site, at sumps L-38, 2L-38 and 3/4/5L-38 and (B) C-42 and B-19. Data collected in August 2022.

All sumps were originally filled with saline drilling muds, so it is unlikely that the differences observed in 2022 (Figure 10A) derive from the original state of the materials deposited in the sump.

The conductivities of pond water samples are 3–4 orders of magnitude higher than the ground conductivities. This is due to the higher conductivity of water in comparison with ice and the presence of salts in the ponds. However, the ground conductivities are comparable to the conductivity of Mackenzie Delta water collected near Inuvik (0.3 mS/cm = 30 mS/m; Burn 1995). Water in the channels of the outer Delta is likely of higher conductivity due to the influence of the proximal Beaufort Sea. The conductivities of pond-water samples, presented in Table 4, show elevated salt concentrations from pools on sumps at Mallik and Niglintgak in comparison with undisturbed terrain. The values from Taglu are comparable between ponds on and off the sump. At Mallik, the conductivity in pond water was highest at L-38 and lowest at 3/4/5 L-38. Given that the ground conductivity values were in opposite rank order, it is possible that there is leakage of saline fluids from the containment chamber into the pools. This is a plausible hypothesis with the data available but requires further investigation, specifically at ponds.

However, unless the 5-m penetration of the EM-31 is insufficient to reach the waste materials, the data presented in Figure 10 suggest that the saline fluids have dispersed from the oldest sumps over the past 40–50 years. The conductivities are now indistinguishable between the sump caps and undisturbed terrain near L-38, C-42, and B-19. The differences between surveys in 2012 and 2022 and the values from 2 L-38 in 2022 indicate that the materials are dispersing from 2 L-38. The high ground conductivity measured at 3/4/5 L-38 and the similarity in conductivity of pond water on this sump to pond water in undisturbed ground, suggest that drilling fluids are relatively well contained in this structure.

It may be a coincidence that the ground conductivities of the Mallik sumps site decline with age, but information from pond water and the comparison of conductivities over time support the hypothesis that the oldest sumps have not performed as intended over the last 50 years. Since the ground conductivity at the three oldest sumps is similar to values measured in undisturbed terrain, these structures may have failed. Further investigation with different tools is required to verify this hypothesis, by direct ground sampling of sump contents or deeper EM penetration (e.g., EM-34 instrument).

8 CONCLUSION

On the basis of the results presented above, we conclude:

1) The electrical conductivity of the ground and pond waters at three sumps in low-lying areas of the outer Mackenzie Delta suggest that sumps built in the 1970s have failed to contain saline waste because the ground conductivity at these sumps is similar to undisturbed ground.
2) The most recent sump, Mallik 3/4/5 L-38, built in 2002, remains clearly distinguishable by its elevated ground conductivity. The conductivity of pond water on the sump is similar to the conductivity of samples from undisturbed ground nearby. This sump appears to be performing relatively well.
3) A sump built in 1998, 2 L-38, has lower conductivity than 3/4/5 L-38. A reduction in the spatial concentration of conductivity at 2 L-38 and elevated concentrations in ponds at this sump suggest that some of this sump's contents may have dispersed between 2012, the date of a previous EM survey, and 2022.

9 Acknowledgments

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