SNOW COVER AND SUBNIVEAN AND SOIL TEMPERATURES AT ABANDONED DRILLING MUD-SUMPS, MACKENZIE DELTA, NORTHWEST TERRITORIES, CANADA

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ABSTRACT

In permafrost terrain, drilling-mud sumps excavated in frozen ground are designed to contain wastes generated by exploratory oil and gas drilling. When drilling operations are complete, the sump is backfilled with excavated materials. Over time, the active layer should re-establish and be maintained in the sump cap, with the deposited contaminants remaining in underlying frozen ground. In this paper, the influence of snow cover on subnivean and permafrost temperatures is investigated at several sumps in alluvial terrain of the outer Mackenzie Delta. The four sumps studied were abandoned in the 1970s. Two sumps have re-vegetated with tall shrubs and two have caps re-vegetated with only low-lying grasses. In March 2005, mean snow cover on the bare sump caps were 56 and 67 cm, with deeper snow drifts around sump perimeters (64 and 103 cm). Adjacent undisturbed terrain had mean snow depths of 31 and 39 cm, respectively. Snow cover on sump caps re-vegetated with tall shrubs was greater than 120 cm. Mean snow depths around the perimeter of the sumps ranged from 88 to 98 cm, but means of 46 and 67 cm were observed in surrounding, undisturbed alluvial terrain. A positive, curvilinear relation was observed between snow depth and subnivean temperatures. Variations in near-surface permafrost temperatures across a sump cap were associated with patterns of snow accumulation. Sites with low snow accumulation, such as sump caps with low-lying grasses and undisturbed terrain with sedge vegetation, were characterized by cold mean temperature at the top of permafrost (MTTop)(> -5 °C). In contrast, areas with high snow accumulation, including sump caps with tall shrubs and sump perimeters, were characterized by MTTop that ranged from -0.5° to -1.0 °C and active-layer depths that exceeded 130 cm. Warming of permafrost as a result of perennial snow accumulation might lead to the long-term thawing of waste within the sump and may promote lateral migration of contaminants. If ice-rich permafrost is degraded, thaw settlement can lead to collapse of the sump cap. The field data demonstrate that in permafrost terrain, sump abandonment practices should consider contouring and reclamation plans that inhibit snow accumulation.

INTRODUCTION

The potential development of a Mackenzie Valley pipeline has led to an increase in oil and gas exploration in the Mackenzie Delta region, Northwest Territories (NWT). In the past, sumps excavated in permafrost have been utilized for disposal of wastes generated during exploratory drilling for arctic oil and gas (French, 1980). There have been 169 wells drilled on land within the Mackenzie Delta region over the last 40 years, and generally, a capped drilling-waste sump has been constructed at each site (AMEC, in press).

In permafrost terrain, sumps are used to contain drilling waste because frozen ground can provide a low permeability medium (Burt and Williams, 1976; French, 1980). Drilling in permafrost terrain requires the addition of potassium chloride (KCl) to the chilled-mud system in order to improve circulation because it depresses the freezing point (Hardy BBT Limited and Stanley Associates Engineering Ltd., 1988). Materials deposited in the sump include drilling fluids, cuttings and rigwash. To facilitate the deposition of drilling wastes, the sump is usually excavated adjacent to the well-head (Thomas et al, 1988). Following completion of drilling, the sump is capped with excavated materials and left to re-vegetate (Drinnan et al., 1987). It is intended that the active layer will re-establish within the sump cap, and that the drilling wastes will remain immobile within the underlying permafrost (Fig. 1).

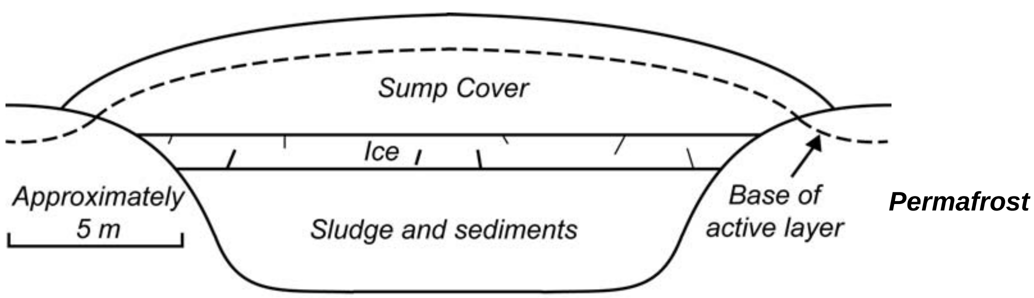


Figure 1: Cross Section of a Drilling Waste Sump (Modified from Dyke, 2001)

Subsidence and ponding on the sump cap indicate permafrost degradation, which may compromise the containment of drilling wastes (Dyke, 2001). Poor sump performance is usually attributed to inappropriate site selection or construction and abandonment practices (French, 1980; Kokelj and GeoNorth, 2002). For example, capping a sump that contains unfrozen muds can cause the wastes to squeeze out the sides. Disturbance of the tundra surrounding a sump can cause the adjacent sump to collapse if the disturbance increases the active-layer thickness, resulting in surface subsidence and ponding. In recent years, drilling operations have been limited to winter to minimize terrain disturbances.

The presence of tall shrubs in the ponds of collapsed sump caps suggests that in some cases, degradation occurred after an initial period of sump stability (Kokelj and Geonorth, 2002). It is well known that snow accumulation can retard ground heat loss in winter (Goodrich, 1982). In permafrost terrain, areas with warmer ground temperatures are generally associated with tall shrubs and slope concavities that accumulate deep snowdrifts (Mackay and MacKay, 1974). This raises the possibility that snow drifting around the caps of drilling mud sumps, and on the top of caps where tall shrubs have grown, may result in active-layer deepening and warming of the underlying permafrost.

In this paper, the patterns of snow accumulation and subnivean temperatures on the tops of, and around the perimeters of abandoned drilling-mud sumps in the Kendall Island Bird Sanctuary (KIBS) are examined (Fig. 2). Subnivean temperature, the temperature at the base of the snow pack, was measured as a surrogate to late-winter ground temperature. Snow depths and subnivean temperatures were collected along transects across four sumps in KIBS. Two of the sumps have re-vegetated with alder and willow, and grasses colonize the remaining two sump caps. Shallow ground temperatures were also collected on the tops and perimeters of sumps with and without shrub vegetation. The main objectives of this paper are: (1) To describe the patterns of snow accumulation across drilling waste sumps; (2) to examine the effect of vegetation on snow accumulation at abandoned sumps; (3) to investigate the relation between snow depths and subnivean temperatures; and (4) to examine the effects of snow accumulation on the thermal evolution of drilling-mud sumps.

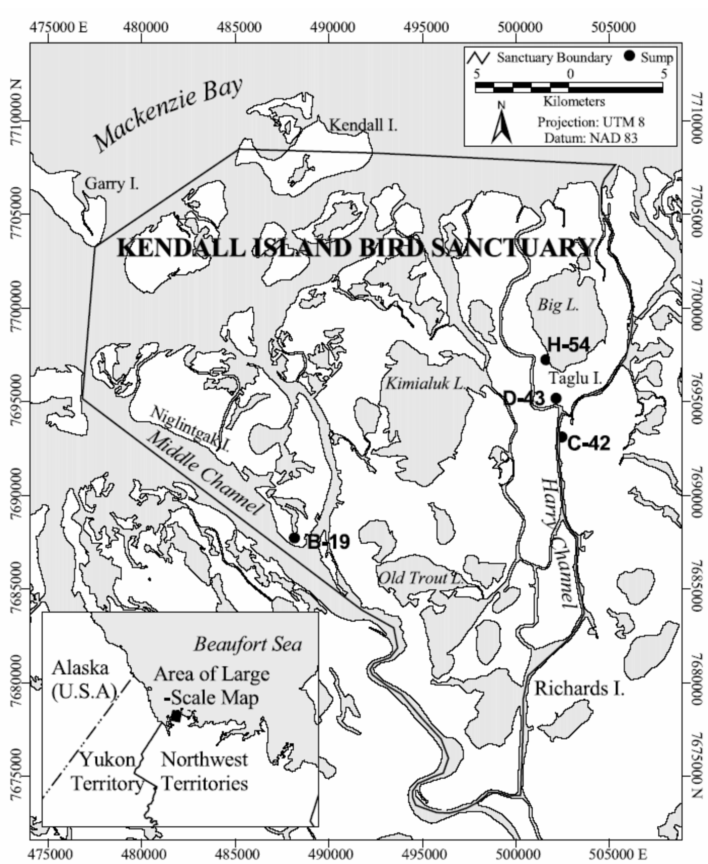


Figure 2: Sump study sites B-19, D-43, H-54 and C-42, Kendall Island Bird Sanctuary, Mackenzie Delta, Northwest Territories

STUDY AREA

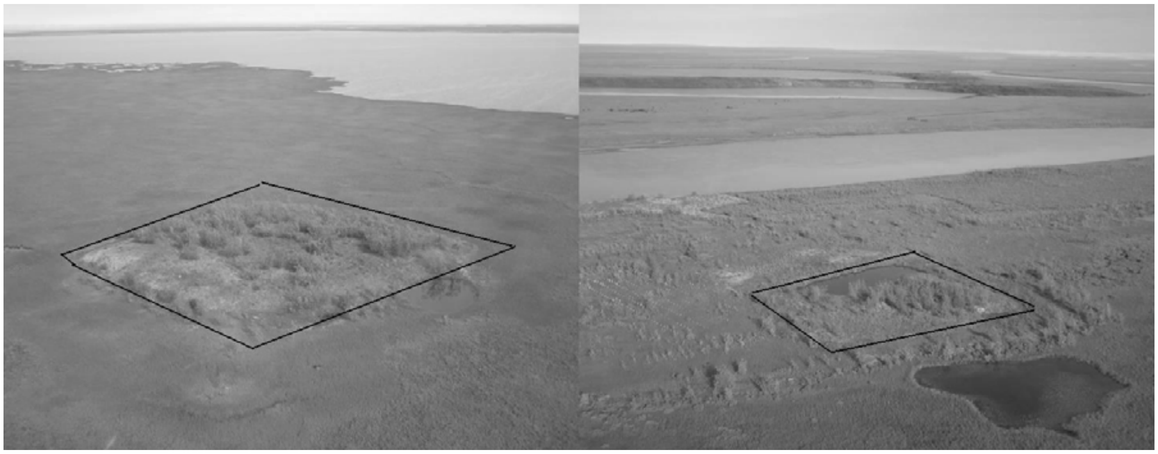
Four sump sites were investigated in the Kendall Island Bird Sanctuary (600 km^2), outer Mackenzie Delta, NWT (Fig. 2). The sanctuary is bounded by Mackenzie Bay to the north, Harry Channel to the east, and Middle Channel to the south and west. Terrestrial environments consist of both alluvial deposits and erosional remnants of the Tununuk Low Hills (Mackay, 1963; Rampton, 1988). Low-lying alluvial deposits comprise much of the terrestrial environment. A complex history of erosion, inundation and deposition of alluvium can explain permafrost thickness in excess of 500 m on Taglu Island (Taylor et al., 2000). Areas with modern deltaic deposits are generally underlain by thinner permafrost due to thermal disturbance as a result of channel shifting (Taylor et al., 2000). Ice wedges and aggradational ice may comprise up to 50% of the volume of near-surface permafrost (Mackay, 1963; Mackay, 1972; Kokelj and Burn, 2005). The outer Delta plain is inundated by spring flooding and summer storm surges (Mackay, 1963). Willows and alder grow on aggrading point bars, and sedges and mosses colonize extensive low-lying wetlands distal from the stream channels (Mackay, 1963). Active-layer thicknesses range from about 60 cm in sedge wetlands to more than 120 cm in willow communities on aggrading point-bars (Tarnocai et al., 2004).

The remnant uplands of the Tununuk Low Hills, characterized by rolling topography, are underlain by permafrost several hundreds of metres thick (Taylor et al., 2000). Earth hummocks are present on hills and slopes, with peat land development in low-lying, poorly drained areas. Aggradational ice, wedge ice and massive segregated ground ice combine to create an ice-rich permafrost environment (Mackay, 1971). Vegetation is low-shrub tundra (Bliss, 2000). In hummocky uplands, active-layer thickness ranges from 30 to 90 cm (Mackay and Burn, 2002).

At Tuktoyaktuk, cold winters last up to eight months (-27.2°C mean January temperature), and the summers are cool (10.9°C mean July temperature) and short (Burn, 2002). Seasonal temperatures, especially in the summer, are influenced by the Beaufort Sea which creates a strong north-south climate gradient when the ice pack depresses air temperatures during on–shore winds (Burn, 1997).The inter-annual variation in distribution and depth of snow at the sanctuary are unknown, but in general, there is more snow inland than at the coast (Mackay, 1993). For example, the mean annual snowfall at Tuktoyaktuk is less than 15 cm but the mean at Inuvik is more than 25 cm (Environment Canada, 2005). North of the treeline, snow is blown from hilltops and accumulates in slope concavities where drifts may be more than 3 m deep (Burn, 2002). In the Mackenzie Delta, local variation in snow accumulation is related to vegetation (Smith, 1975).

STUDY SITES

Detailed investigations were conducted at four sites in alluvial terrain of the outer Mackenzie Delta (Fig. 2). Two sumps, H-54 and C-42, have re-vegetated with willows approximately 3 m in height (Fig. 3). The other two sumps, B-19 and D-43, have re-vegetated only with grasses (Fig. 4). The sump at well site H-54, constructed in 1976, is located in alluvial terrain with low-centred polygons. Site D-43 is located a few kilometres to the southeast in similar terrain. Much of the delta plain on Taglu Island is colonized by sedge wetland. The sump at well site C-42 was drilled in 1972 and is located a few hundred metres to the east of Harry Channel. Low-lying willows grow on the alluvial substrate. Well B-19, drilled in 1975, is located on the southeast corner of Niglintgak Island. This area is underlain by low-centred polygons in alluvial silts. This site is regularly inundated by summer storm surges.



H-54 **C-42**

Figure 3: Sumps H-54 and C-42 with tall shrubs growing on the caps. H-54 is located in a wetland sedge environment and is approximately 110 m in length. C-42 is located in a low-lying shrubby environment. The sump cap is approximately 60 m in length.

B-19 **D-43**

Figure 4: Sumps B-19 and D-43 with low-lying grasses growing on the sump caps. B-19 is located in a wetland sedge environment and is approximately 80 m in length. D-43 is also located in a wetland sedge environment and the remaining sump cap is approximately 40 m in length.

FIELD METHODS

In March 2005, snow depths and subnivean temperatures were determined at each of the four study sites (Fig. 2). Surveys were completed along transects established during the summer of 2003 and 2004. Transects oriented north-south and east-west extended across sump tops into adjacent undisturbed terrain.

Snow depths (cm) were collected at 5 or 10 m intervals along transects by pushing a calibrated dowel to the depth of refusal. Subnivean temperatures were collected at regular intervals along each transect. Thermistors attached to the base of dowels were pushed down to the snow/ground-surface interface and allowed to equilibrate for 15 minutes. Resistivity measurements were obtained using a multi-meter and subnivean temperatures were estimated using the following formula:

$$T = -19.271 * [ln (x * 1000)] + 171.59 \qquad [1]$$

where T is temperature (°C), x is resistivity (Ω) and *ln* is natural logarithm.

Ground temperatures were measured on the tops and perimeters of vegetated and unvegetated sump caps and in adjacent undisturbed terrain from September 2003 to August 2004. The measurements were made at two-hour intervals with thermistors (Onset Computing, HOBO™, TMC6-HA) connected to data loggers (Onset Computing, HOBO™, H08-006-04). Two thermistors at each location were positioned at 5 cm depth and near the top of the permafrost by attaching the sensors to a dowel, and inserting it into a hole augered into the frozen ground.

RESULTS

Snow Depths

Snow depths were collected on the sump top, perimeter and in adjacent undisturbed terrain at B-19 and D-43. Figure 5 indicates that mean snow depths on the unvegetated caps were 56 and 67cm (standard deviations were 16 and 39 cm). The deepest snow was encountered around the sump perimeters (Fig. 5). The mean snow depth around B-19 was 64 cm with a standard deviation of 14 cm, and the mean at D-43 was more than 100 cm with a standard deviation of 20 cm. Around the perimeter of D-43, the deeper snow can be attributed to the greater cap relief and to the presence of shrubs adjacent to the sump. In contrast, the B-19 cap is more gently feathered, and shrubs which may trap snow are absent. Undisturbed terrain surrounding both sumps consists of sedge-wetlands with low-centred polygons. Mean snow depths in terrain adjacent to B-19 and D-43 were 31 and 39 cm, with standard deviations of 11 and 9 cm, respectively (Fig. 5).

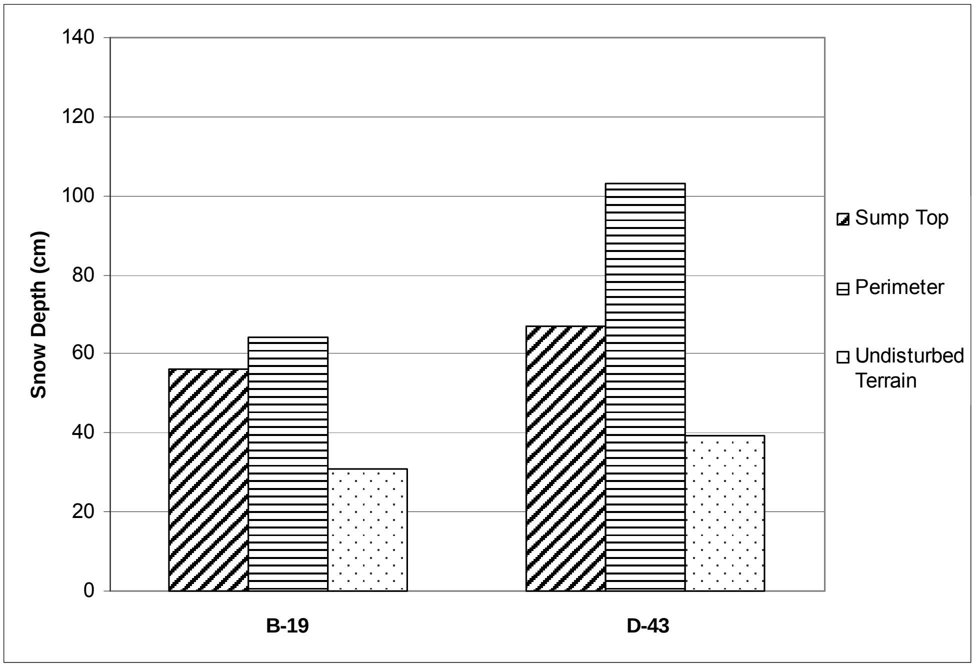


Figure 5: Mean snow depths at the top, perimeter, and in adjacent undisturbed terrain for two unvegetated sumps, B-19 and D-43.

Snow depths were also collected on the cap, perimeter and adjacent undisturbed terrain at vegetated sumps H-54 and C-42. Snow was significantly deeper at these two sites and the depth frequently exceeded the 120 cm length of the probe (Fig. 6). Of thirty-eight sample points on the sump top at H-54, thirty-three reported depths were greater than 120 cm, while eight of fifteen sample points on the sump top at C-42 reported values greater than 120 cm. The mean snow depths around the perimeters of H-54 and C-42 were 98 and 88 cm, with standard deviations of 21 and 30 cm, respectively. In adjacent undisturbed terrain, mean snow depths at H-54 and C-42 were 46 and 67 cm, and respective standard deviations were 13 and 16 cm. The relatively deep snow in terrain adjacent to C-42 is related to the trapping of snow by the low shrubs which surround the site. In contrast, H-54 is located in a sedge-wetland environment from which snow may be removed by winter winds.

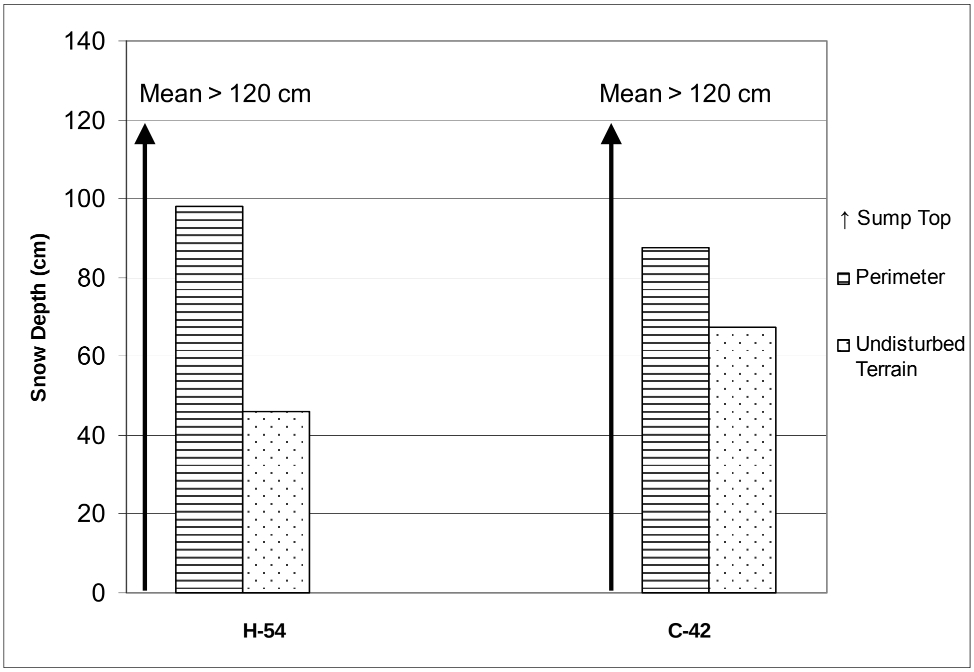


Figure 6: Mean snow depths on the top, perimeter, and in adjacent undisturbed terrain for two vegetated sumps H-54 and C-42.

Snow depth and subnivean temperatures

To investigate the influence of snow accumulation on ground-surface temperature, snow depth was plotted against subnivean temperature collected from the tops, perimeters and adjacent undisturbed terrain at B-19, D-43, and C-42 (Fig. 7). Data from the H-54 sump was not utilized in this analysis as subnivean temperatures were not collected at this site. The relation between snow depth and temperature below 0 °C is described by:

$$y = 8.569 \ln(x) - 43.524 \qquad [2]$$

where y is temperature, *x* is snow depth and *ln* is natural logarithm.

In 2005, mid-March subnivean temperatures at sites with less than 30 cm snow were generally below -15°C. Subnivean temperatures at sites with more than 100 cm of snow were above -5°C. The warm subnivean temperatures are related to the insulative effect of snow. Snow inhibits near-surface cooling by eliminating direct exposure of the ground to cold winter air temperatures, reducing the upward flow of latent heat from freezing of the active layer. Furthermore, latent heat supplied by freezing of warm permafrost prevents near-surface temperatures from cooling in late winter (Karunaratne and Burn, 2004).

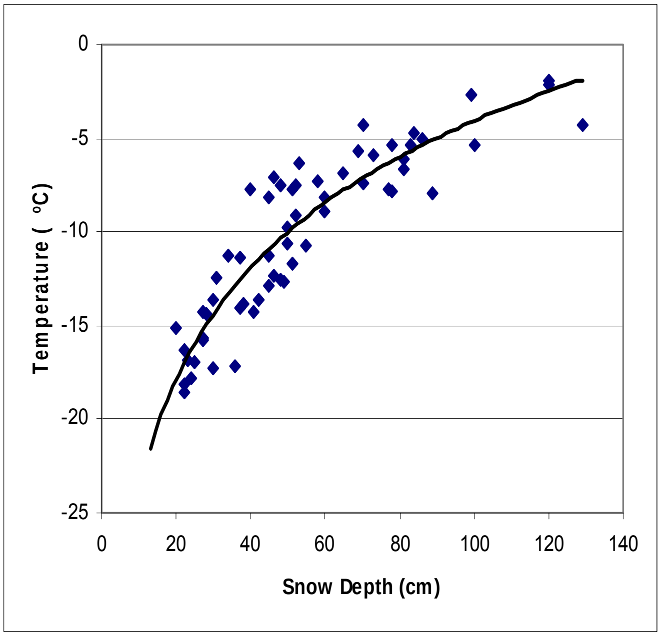


Figure 7: Relation between snow depth and subnivean temperature

Ground temperatures at abandoned sumps

Table 1 indicates vegetation cover, end of winter snow depths, active-layer depths and mean annual ground temperatures at the top of permafrost (MTTop) for sumps D-43 and C-42. Field data for the tops, perimeters and adjacent undisturbed terrain are presented for the two sites.

The MTTop of the wetland sedge environment adjacent to D-43 was -5.4°C (Table 1). Snow from the cap top is removed by winter winds, promoting ground cooling in winter (Fig. 5, Table 1). Mean TTop on the sump cap was -5.0°C. The perimeter of D-43 accumulates deep winter snow drifts, the MTTop is above -1.0°C, and the active layer is deep (>110 cm).

Sump C-42 is located a few kilometres away in alluvial terrain with low willows. The MTTop in undisturbed terrain is -3.0°C. Snow accumulation due to the presence of low willows at C-42 can account for ground temperatures that are warmer than at the wetland sedge community around D-43 (Fig. 5 & 6, Table 1). The sump cap at C-42 has re-vegetated with tall willows, resulting in thick snow accumulation on the sump cap and around the perimeter (Fig. 6, Table 1). Thaw depths at these two locations were greater than 130 cm (Table 1). The mean permafrost temperatures at the cap and at the perimeter were only -0.7°C and -0.8°C, respectively.

Table 1: Vegetation cover, snow depths, active layer depths, and mean annual temperature at the top of permafrost for a vegetated (C-42) and an un-vegetated sump (D-43), August 2003 to September 2004.

	Vegetation Cover	Snow Depth (cm)	Active Layer Depth (cm)	Mean Annual Temperature Top of Permafrost (°C)
D-43				
Sump Top	Grasses	30-50	90-110	-5.0
Perimeter	Low Shrub (1m)	120-180	110-135	-0.9
Undisturbed	Sedge/wetland	50-70	30-50	-5.4
C-42				
Sump Top	Tall Shrub (up to 3m)	100-160	>130	-0.7
Perimeter	Shrub (1m)	150-200	>130	-0.8
Undisturbed	Shrub (1m)	60-80	80	-3.0

DISCUSSION

In windswept arctic environments, vegetation and topography are important factors that affect the nature and distribution of snow cover (Figs 5, 6, Table 1) (Mackay and MacKay, 1974; Smith, 1975). Development of infrastructure and re-vegetation of anthropogenic disturbance may modify natural snow conditions. This study indicates that the positive relief of a sump can promote the collection of snow around the cap perimeter (Figs 5, 6). At C-42 and H-54, tall willows on the sump tops are associated with snow depths greater than 120 cm (Fig. 6). At sump caps without shrubs (D-43 and B-19), snow was hard packed and shallow in depth (Fig. 5).

Subnivean temperature has a positive, curvilinear relation with snow accumulation (Fig. 7). Figure 7 indicates a steep increase in subnivean temperatures as snow depth increases to a depth of about 60 cm. An inflection in the curve at about 60 cm snow depth suggests that subsequent increases in snow depth have less influence on subnivean temperature (Fig. 7). The same relationship was seen by Smith (1975) in the Mackenzie Delta.

Temperature data from the top of permafrost suggest that snow depth is a key factor influencing variation in ground temperatures within and between the study sites (Table 1). Mean annual ground temperatures at the top of permafrost ranging from -0.5° and -1.0°C were measured at locations with snow depths greater than 100 cm (Table 1). These locations included sump perimeters and sump tops with tall shrubs (Figs 5, 6, Table 1). Thick snow accumulation inhibits freeze-back of the active layer. Latent heat from cooling of warm permafrost, in the presence of insulative snow cover, inhibits near-surface cooling later on into the winter (Karunaratne and Burn, 2004). Colder permafrost temperatures were seen at locations with low snow cover, such as sump caps with low-lying grasses, and undisturbed terrain with sedge vegetation (Figs 5, 6, Table 1). Thermal modeling is being undertaken to determine if permafrost can be sustained given the boundary conditions observed at the perimeters and tops of drilling mud sumps (Table 1).

Management of construction and abandonment practices play a key role in sump integrity (Kokelj and GeoNorth, 2002). However, the intention of a sump is to contain wastes in perpetuity, thus, effective management of these sites should also consider longer-term causes of sump degradation. Data indicate that perennial snow accumulation around and/or on top of a sump, will, over time, cause permafrost temperatures to warm and active-layer thickness to increase. This may lead to thawing of saline fluids within the sump and potential problems with site integrity. The notion that sump degradation can be a gradual process is supported by the observation of large shrubs submerged in ponds on, or adjacent to, degrading sump caps (Kokelj and GeoNorth, 2002).

It should be recognized that perennial accumulation of deep snow might contribute to long-term problems with abandoned drilling-mud sumps, irrespective of construction techniques and climate variation. Proper contouring of sumps to inhibit snow accumulation around perimeters should be considered. Furthermore, reclamation programs should avoid plans to re-vegetate sumps in permafrost terrain with vegetation that would enhance snow accumulation.

CONCLUSIONS

Construction and abandonment practices are the most important factors dictating success or failure of drilling-mud sumps in permafrost terrain (French, 1980). However, data suggest that long-term warming of permafrost may occur in response to increased amounts of perennial snow accumulation around the sump caps and on the tops due to the growth of tall shrubs. Based on this study, the following conclusions can be made:

1. Sump caps are positive relief features that promote the accumulation of snow at the perimeter;
2. Growth of tall standing vegetation (shrubs) on the sump cap will promote snow accumulation;
3. A positive curvilinear relation was observed between snow depth and subnivean temperature at the study sites. In March 2005, snow depths greater than about 100 cm were associated with subnivean temperatures warmer than -5.0°C.
4. Thick snow accumulation can retard ground-heat loss in winter. Perennial snow accumulation around the perimeters and on the tops of sump caps with tall shrubs can result in warming of the permafrost and an increase in thaw depth.
5. To promote the long-term stability of sumps in permafrost terrain, efforts should be made to inhibit the growth of tall shrubs that may enhance snow accumulation. Contouring of the cap should be considered to inhibit snow drifting around the sump perimeter.

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