Review of current research on drilling-mud sumps in permafrost terrain, Mackenzie Delta region, NWT, Canada.

Julian C.N. Kanigan & Steven V. Kokelj
Indian and Northern Affairs Canada, Yellowknife, NT, Canada

ABSTRACT
Sumps in the Mackenzie Delta region of the Northwest Territories are intended to encapsulate drilling wastes within frozen ground, but subsidence of sump covers suggests that the permafrost has degraded. Recent research on drilling-mud sumps in permafrost is reviewed to assess key factors related to sump performance. Mean permafrost temperature is significantly associated with sump integrity, and can supersede the effect of sump closure practices. Tall shrubs and deep snow on the sump cap play an important role in the thermal evolution and long-term integrity of drilling-mud sumps. Climate warming is also likely to have significant impacts on drilling-mud sump integrity. These studies suggest the importance of a long-term sump management approach.

RÉSUME
Des bassins à boues de forage dans la région du delta de Mackenzie des Territoires du nord-ouest sont prévus pour encapsuler des pertes de perçage dans le pergélisol, mais l'affaissement des couverts de bassins à boues de forage suggère que le pergélisol a dégradé. La recherche récente sur des bassins à boues de forage de perçage-boue en pergélisol est évaluer pour des facteurs clé liés à l'exécution de bassin à boues de forage. La température moyenne de pergélisol est associée de manière signicative à l'intégrité de bassin à boues de forage, et peut remplacer l'effet des pratiques en matière de fermeture de bassin à boues de forage. Les grands arbustes et la neige profonde sur le bassin à boues de forage jouent un rôle important dans l'évolution thermique et l'intégrité à long terme des bassins à boues de forage de boue de perçage. Le réchauffement climatique peut également avoir des impacts significatifs sur l'intégrité des bassins à boues de forage de perçage-boue.

1 INTRODUCTION

Sumps have been constructed to contain wastes associated with exploratory oil and gas drilling in northern Canada since the 1920's (Nassichuk 1987), and in many northern jurisdictions sumps remain a regulated drilling waste disposal option today. In permafrost terrain, the design intention of a sump is to immobilize saline drilling wastes by encapsulating them within permafrost (Figure 1) (Imperial Oil Resources Ventures 2004). Drilling fluids are deposited in the sump and backfilled with the excavated materials. However, if the drilling fluids are not completely frozen when the sump is being capped, they may be squeezed out of the sides (French 1978a, 1978b, 1980). Capping materials excavated from near-surface permafrost are often ice-rich so that reestablishment of an active layer in the cap can lead to significant thaw subsidence and ponding (Figure 2). The ensuing thermal disturbance may promote further active-layer deepening and the eventual loss of drilling-mud containment (Dyke 2001). Uncontained saline drilling fluids can alter soil chemistry and inhibit vegetation growth (Johnstone and Kokelj 2008). Managing the long-term integrity of drilling-mud sumps is a priority for communities, resource managers and industry who wish to minimize the environmental impacts of hydrocarbon exploration and development.

Oil and gas exploration in the Mackenzie Delta region of the Northwest Territories (NWT) since the late 1960's has resulted in over 150 legacy sumps (Figure 3) (AMEC Earth and Environmental 2005). The majority of sumps

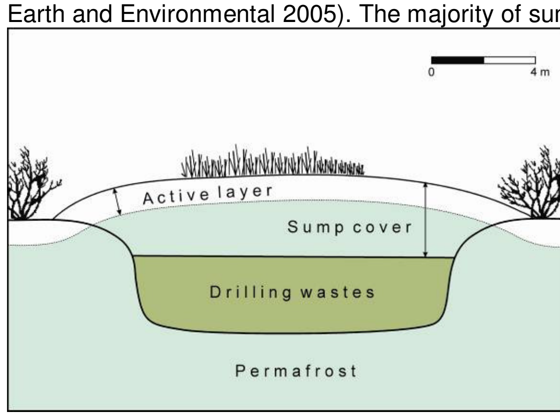

Figure 1 Configuration of a sump to encapsulate drilling wastes in permafrost (from Jenkins et al. 2008, Fig. 1).

(70%) were constructed between 1970 and 1980 (Jenkins et al. 2008). The most recent sump was constructed in 2007; however, due to public concern over the impacts of sumps in the region, many companies have recently opted to transport drilling wastes by truck to disposal facilities outside of the NWT. Community concern regarding sump performance and industry and government interests related to a proposal for a pipeline in the region has renewed research and monitoring efforts related to drilling-mud sumps.

The objective of this paper is to review and synthesize recent research on drilling-mud sumps in permafrost terrain. The review will: 1) Characterize site conditions at

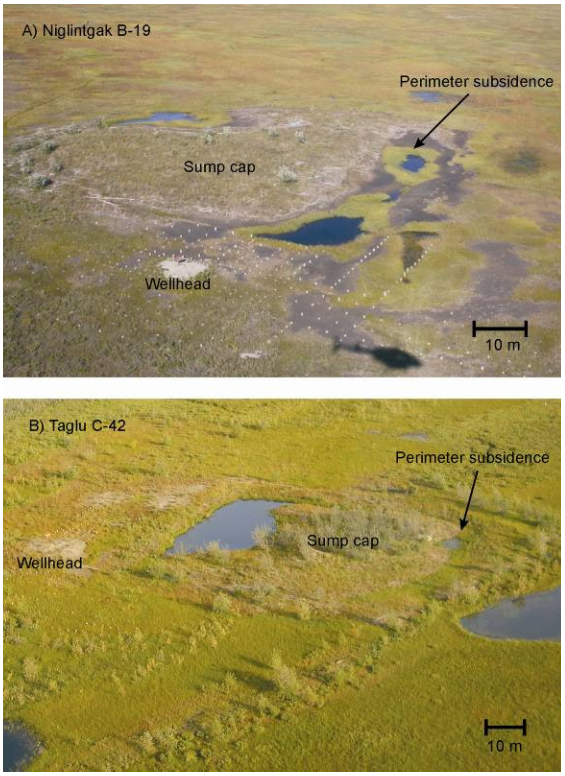

Figure 2 1970's era sumps located in the delta floodplain with perimeter subsidence and ponding. The sump cap at A) is characterized by short grasses and sedges and perimeter ponding; and B) is characterized by tall shrub vegetation and significant cap ponding.

sumps in the Mackenzie Delta region; 2) Assess the relative effect of environmental conditions and construction practices on sump integrity; 3) Discuss the effect of site-scale environmental factors on sump performance; and 4) Summarize the implications of the reviewed research on sump management.

2 MACKENZIE DELTA STUDY AREA

The Mackenzie Delta region encompasses a variety of environmental conditions that can affect sump performance. The greatest contrast in environmental conditions is between the annually flooded delta plain and the uplands east of the delta (Figure 3), where the majority of drilling-mud sumps (77%) are located (Jenkins et al. 2008). The entire delta is an area of continuous permafrost (Nguyen et al. 2009), but due to the warming influence of thousands of lakes and shifting channels, the ground is generally warmer in the delta floodplain than in the adjacent uplands. Mean annual ground temperatures (MAGT) in the delta range from -1.5 to -5°C (Burn and Kokelj 2009). The uplands are generally colder, with MAGT's decreasing northward from -3°C near Inuvik, to -7°C on the tundra near Tuktoyaktuk (Burn and Kokelj 2009). Drilling-mud sumps constructed in ground close to 0°C are more susceptible to thaw if conditions change (Kokelj et al., 2010). A comparison of current MAGT's with those in the 1970's shows that while upland ground temperatures have increased by 1 to 2°C in association with regional warming of air temperatures (Burn and Kokelj 2009), those in the delta floodplain have remained relatively unchanged because of the reduced response of lake-bottom temperatures to climate warming (Kanigan et al. 2008).

Surficial sediments of the delta floodplain are a uniform sandy silt deposited during spring flooding (Kokelj and Burn 2005), while those of the uplands are generally fine-grained lacustrine, alluvial or glacial sediments (Rampton 1988). Permafrost is ice-rich throughout the region. Pore ice, wedge ice and segregated ice lenses in the upper 2 to 3 m of permafrost are present in both delta and upland sediments (Williams 1968, Kokelj and Burn 2004, 2005, Morse et al. 2009). Massive tabular ice bodies are encountered below the till layer in the uplands (Mackay 1963, Rampton 1988). Near-surface ground ice is a key factor in the geotechnical sensitivity of sumps in permafrost terrain since ground ice that is disturbed or exposed by sump construction can melt and cause subsidence.

3 REVIEW AND SYNTHESIS

3.1 Mackenzie Delta Drilling-mud Sump Assessment

In response to considerable stakeholder concern with respect to drilling-mud sumps in the Mackenzie Delta region, the Environmental Studies Research Fund (ESRF) supported a complete desktop inventory of sumps in the Inuvialuit Settlement Region (AMEC Earth

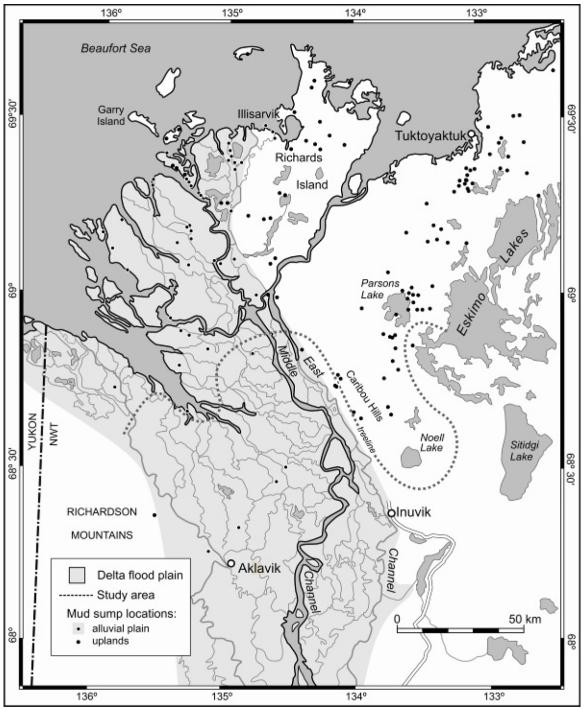

Figure 3 Drilling-mud sumps in the Mackenzie Delta region (from Kokelj et al. 2010, Figure 1).

and Environmental 2005). A field protocol to characterize drilling-mud sumps and related environmental conditions was developed by a multi-party advisory group including Inuvialuit, industry, regulators and scientists. Industry and the ESRF adopted the protocol to assess the majority (110) of drilling-mud sumps in the Mackenzie Delta region (AMEC Earth and Environmental 2005, Komex International and IEG Environmental 2005, 2006). The resulting geographic database is publically available from Indian and Northern Affairs Canada at ssc-btc.inac.gc.ca/sumps. The drilling-mud sump assessment addressed a significant public concern and yielded a large, accessible environmental dataset that has been used as a basis for industry risk assessments and to investigate sump conditions and cap integrity (Jenkins et al. 2008).

3.2 Site Conditions

Field assessments included an electromagnetic (EM-38) survey at each site to help determine the presence and distribution of salinity (Komex International and IEG Environmental 2005, 2006). The EM-38 is a geophysical tool which can be used to delineate areas of relatively high conductivity in the upper 1.5 m of the ground, which are often related to the presence of salts. Visual assessment of EM-38 images (Figure 4) showed that almost three-quarters (74%) of the sumps had zones of elevated conductivity beyond the confines of the sump cap, but at more than half (62%) of these sites the areas of high conductivity were located within 30 m of the cap, well within the lease area. Soil samples confirmed the relation between areas of high conductivity and soil salinity at almost all (95%) of the affected sites.

The close proximity of salts to the sump cap may be explained by shallow (<1 m), wide (>30 m) depressions

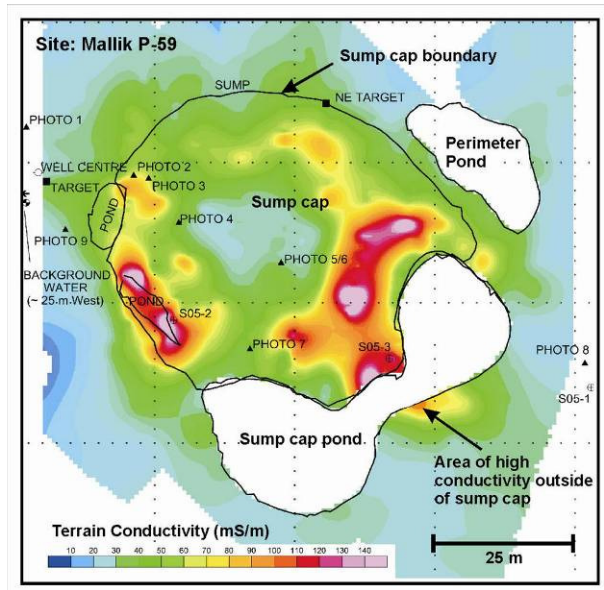

Figure 4 Results of an EM-38 survey at a sump with evidence of salt contamination outside of the cap.

observed around many sumps (Figure 2). These depressions are likely due to thaw subsidence resulting from surface disturbance during exploration drilling activities (Johnstone and Kokelj 2008, Kokelj et al. 2010). The EM-38 surveys proved to be a useful initial assessment tool to detect the presence of salinity at a site, and showed that the majority of delta sumps exhibit localized areas of elevated salinity adjacent to the sump. The maximum extent of most of the EM-38 surveys was about 40-m from the cap edge. In future assessments, at sites where salinity is detected outside of the sump cap, it would be useful to survey the full extent of the area of elevated salinity.

Site assessments also included an evaluation of sump-cap integrity, which was determined by estimating the areal extent of cap collapse and ponding (Figure 2) (Komex International and IEG Environmental 2005, 2006). Significant ponding that could likely lead to thawing of sump contents was defined as occupying greater than 20% of the sump cap. About one-third (31%) of the sumps exhibited significant cap ponding (Jenkins et al. 2008). The majority (93%) of these sumps are at least 30 years old, which could illustrate the deterioration of sumps over time, or reflect improvements to sump construction practices in recent decades.

3.3 Effect of Construction Practices and Environmental Conditions on Sump Performance

The relative influence of sump construction practices and environmental conditions on sump integrity was examined using the field assessment data from sumps over 30 years old to control for the effects of sump age (Jenkins et al. 2008). Over the past three decades, sump construction and closure practices have improved based on research, building experience and changing land-use regulations (French 1980, 1985). For instance, summer sump operations are no longer permitted due to problems associated with ground thaw and capping unfrozen materials. The last summer sump operation permitted in the delta region was in 1986 (AMEC Earth and Environmental 2005). Environmental conditions associated with site selection have also been linked to sump performance (Kokelj and Genorth 2002). Areas of cold permafrost are more likely to maintain sump contents in a frozen state, whereas areas with warm permafrost are more susceptible to thermal degradation following disturbance (Smith and Burgess 2004).

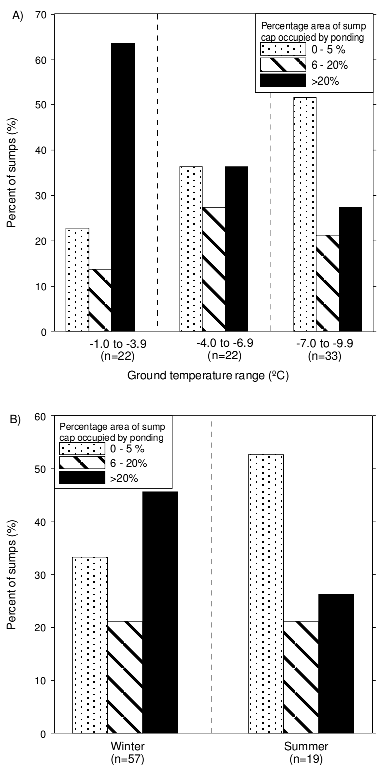

Figure 5 Relations between sump-cap ponding at sumps constructed between 1968 and 1977 and A) mean annual ground temperature; and B) timing of sump closure (modified from Jenkins et al. 2008, Figures 5 and 6).

In warm permafrost (>-4.0°C) of the alluvial delta floodplain, the majority of sumps had significant cap ponding, whereas the zone of coldest permafrost (<-7.0°C) on northern Richards Island and the Tuktoyaktuk Coastlands had the lowest proportion of sumps with significant ponding (Jenkins et al. 2008) (Figure 5A). Sump-cap ponding and MAGT were statistically associated by a test of independence. Unexpectedly, no significant association was found between the timing of sump closure and sump-cap ponding. The majority of sumps capped in the thaw season remained intact (Figure 5B), suggesting that other factors, such as environmental conditions may be a more important determinant of long-term sump-cap integrity. Closer inspection of the data revealed that the effect of mean permafrost temperature overwhelms the impact of sump closure timing: Almost all of the sumps closed in the summer were located in cold permafrost.

The conclusion that sumps in cold permafrost are more stable is supported by thermal modeling which compared the effects of climate warming (0.09°Ca^{-1}) on sump thermal conditions in warm (-3.0°C MAGT) and cold (-6.0°C MAGT) permafrost, respectively. (Kokelj et al. 2010). In a warming climate, the top of the drilling fluids (3.5-m depth) in warm permafrost thawed within a few decades, but in cold permafrost the drilling fluids remained frozen after four decades.

Under current practice, sumps must be capped prior to the end of the winter operating season. Regional climate data documents recent climate warming, particularly at the end of winter. Decadal mean, maximum and minimum air temperatures for the end of the winter operating season from April 1 to 15 for Inuvik and Tuktoyaktuk have increased by about 4°C over the last three decades (Table 1). Warmer late winter conditions could mean that drilling fluids that are typically deposited at the end of the season may not be completely frozen before they are capped. For example, Figure 6 shows that saline drilling fluids in a sump that was capped in April 2005 were close to 0°C and due to a depressed freezing point, were not likely ice bonded at the time of sump capping. Electromagnetic surveys at this sump suggest that some

Table 1 Mean, maximum and minimum air temperatures from April 1-15 for the decades 1970-79 and 1996-2005.

	Inuvik		Tuktoyaktuk	
April 1-15 temperature (°C)	1970-1979	1996-2005	1970-1979	1996-2005
Mean	-18.3	-14.2	-21.1	-17.3
Maximum	-11.1	-2.8	-14.5	-7.9
Minimum	-24.4	-18.8	-26.8	-21.0

(Environment Canada 2010)

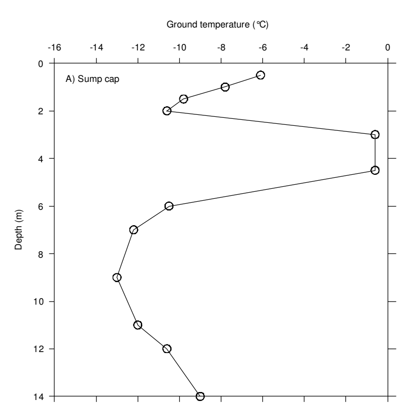

Figure 6 Ground temperatures at a sump after being capped in April 2005. Temperatures are relatively warm from 3 to 5 m, the depth of the drilling fluids.

saline materials are present beyond the confines of the sump perimeter, despite good cap integrity. Capping unfrozen drilling muds can lead to their upward displacement and release into the environment. Climate warming at the end of winter may further restrict an already short operating season since sumps will need to be capped earlier in the season when drilling fluids can reliably be frozen.

3.4 Effect of Site-scale Environmental Conditions on Sump Performance

About one-third of sumps constructed in ideal conditions characterized by cold permafrost and winter sump closure exhibit significant cap performance issues. This suggests that site-scale factors also play an important role. Deeper snow depths on sump caps vegetated by tall shrubs and around the sump perimeter are related to reduced ground heat loss, ground warming and long-term cap subsidence (Johnstone and Kokelj 2008, Kokelj et al. 2010).

Environmental variables were measured at 7 sumps on transects extending from the sump cap into undisturbed terrain (Johnstone and Kokelj 2008). Sump caps vegetated with tall shrubs captured more snow and had deeper active layers than sumps with short vegetation or the undisturbed tundra (Figure 7). Deeper snow and active-layer depths were also recorded immediately adjacent to the sumps (Johnstone and Kokelj 2008). Shrubs often establish and thrive on recently constructed sump caps because the exposed mineral soils provide a seed bed and nutrients that were previously frozen in the upper layer of permafrost. Windblown snow is trapped by the shrubs and the elevated profile of a sump cap can enhance snow drifting around the perimeter. Temperatures at the top of permafrost in 2005/06 at four sump caps with tall and short vegetation were compared (Figure 8) (Kokelj et al. 2010). The two sumps with tall shrubs had mean end-of-winter snow depths exceeding 1 m and 100-cm depth ground temperatures remained above -2.5°C throughout the winter. The two sumps with short vegetation on the sump cap had mean end-of-winter snow covers of less than 50 cm and 100 cm ground temperatures cooled rapidly to below -10°C.

A ground thermal model was used to assess the effect of gradually increasing the snow depths on the sump cap in warm (MAGT -3°C) and cold (MAGT -6°C) permafrost (Kokelj et al. 2010). Snow was increased from 0.17 m to 1.5 m over 3 decades to simulate changes associated with vegetation succession from bare ground of a recently-capped sump to tall shrubs associated with a 30 year-old sump. In both the warm and cold permafrost scenarios, increasing snow depths caused the top of drilling muds (3.5-m depth) to thaw within 40 years. Combining the effect of climate warming (0.09°Ca^{-1}) with increasing snow accumulation resulted

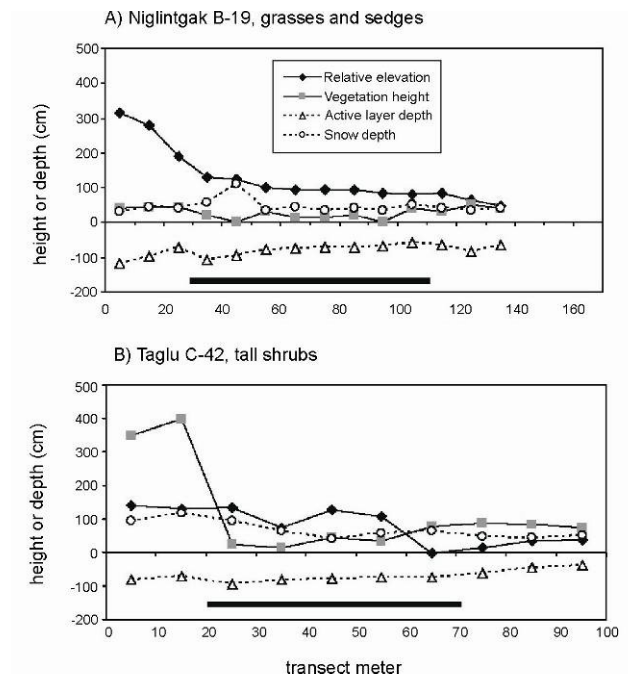

Figure 7 Environmental conditions along transects measured from the sump cap into undisturbed tundra at two study sites corresponding with Figure 2, with contrasting vegetation on the sump cap. The black bar represents the sump perimeter (modified from Johnstone and Kokelj 2008, Figure 5).

in drilling-mud thaw within three decades in both scenarios. The model supports field evidence that the establishment of tall shrubs and increasing snow accumulation on the sump cap can lead to sump thermal degradation, particularly under warming climate conditions.

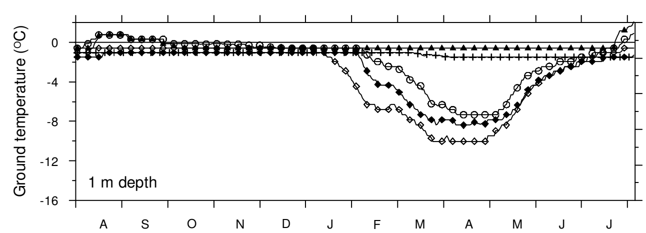

Figure 8 Top of permafrost temperatures for undisturbed tundra (◊), sump caps with low snow (D43 (○), B19 (♦)), and high snow (C42 (+), H54 (▲)) in 2005/2006. Symbols are plotted at 6-day intervals for clarity (modified from Kokelj et al. 2010, Figure 5).

4 DISCUSSION

Analysis of data from the Mackenzie Delta sump assessment and related research resulted in several key considerations for northern sump management. EM-38 survey data indicated that many sumps in the Mackenzie Delta region exhibit areas of high salinity outside of the sump cap, but that in most cases the salinity is

contained within the lease area. About one-third of sumps had a large area of ponding on the sump cap indicating a high likelihood of thawing of sump contents below. These two
methods of assessing sump performance can assist industry and resource managers to establish risk management criteria to identify sumps requiring monitoring or remediation.

Analysis of the relative impact of construction practices and environmental conditions on sump-cap integrity showed that mean permafrost temperature has a significant effect on long-term sump integrity. In the delta region, sump construction should be avoided in the warm delta floodplain. Conversely, sump cap integrity is more easily achieved in the colder permafrost of the uplands. Tall shrubs on the sump cap and raised cap topography were associated with deeper snow and sump warming. This implies that tall vegetation on the sump cap should be discouraged and that sump caps should be contoured to blend with natural topography. Research should be conducted to test if the removal of tall shrubs from a sump cap would lower ground temperatures within the sump, as this could be an effective long-term management strategy.

The process of development of the Mackenzie Delta sump assessment protocol is a useful model for the development of research and assessment programs that benefit and include all stakeholders (AMEC Earth and Environmental 2005, Komex International and IEG Environmental 2005, 2006). It was an imperative first step for a broad spectrum of interested parties to share knowledge and identify key issues pertaining to drilling-mud sumps. An ESRF technical advisory group consisting of Inuvialuit, government, scientists and industry representatives was tasked with developing a sump assessment protocol and setting the scope for sump assessments. Representatives on the working group communicated progress with respective stakeholder groups. This inclusive process may have proceeded more slowly than if one group had worked alone, but unlike a unilateral project, the approach, data collection and results of the assessment project were more broadly accepted. Inclusion of a wide variety of perspectives resulted in broad research and resource management questions that could be addressed by the assessment data. For instance, investigation of sump issues required expertise in permafrost conditions, ecological impacts and soil chemistry. Results were organized and managed in a database (ssc-btc.inac.gc.ca/sumps/index-su-eng.asp). It was particularly important that the results were made accessible to environmental managers in governments and industry as the information can support decision making and provide direction for new policy or regulation.

5 SUMP MANAGEMENT IMPLICATIONS

Based on the review of current research in the Mackenzie Delta region, the following conclusions have been made regarding future sump construction and legacy sump monitoring and management: 1) Stakeholders need to define drilling waste disposal objectives before sump construction.; 2) Warm permafrost is not an effective medium for long-term encapsulating wastes; 3) Future sump proponents should be able to demonstrate that frozen conditions will be maintained at the proposed site, particularly under a climate warming scenario; 4) Removal of tall shrubs from sump caps could help to maintain frozen conditions in the drilling wastes; 5) Elevation of the sump cap should resemble the surrounding terrain to reduce snow accumulation around the edges and thermal degradation; 6) Documented regional climate warming is shortening the amount of time available to freeze back drilling wastes in the late winter. Sumps should be capped earlier in the winter and equipment removed from site to avoid terrain disturbance; and 7) Since multiple factors can affect sump performance, there is a need for long-term monitoring plans and a commitment from industry for long-term site maintenance.

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7 ACKNOWLEDGEMENTS

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