

Drilling Mud Sumps in the Mackenzie Delta Region:

Construction, Abandonment and Past Performance

Submitted To

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Executive Summary

An assessment of sump performance indicated that approximately 50% of sumps constructed in the Mackenzie Delta region during the 1970's have collapsed or are actively collapsing. Degradation of the sump cap indicated that drilling wastes were no longer immobilized in frozen ground. Construction and abandonment practices had clear impact on long-term sump performance. In particular, disturbance to surrounding terrain led to ponding around the perimeter of well-capped sumps, resulting in a thermal disturbance. In many cases this surface ponding initiated the progressive collapse of a sump. The data did not indicate a clear relation between the timing and duration of sump operation and long-term sump stability. However, site assessments did suggest that several sumps have subsided after several years of stability. Snow accumulation around the edges of the sump and enhanced snow cover associated with revegetation of sump caps may affect the thermal regime of a sump. This investigation indicated that regional environmental conditions influence sump integrity. For example, warm permafrost temperatures and frequent flooding in Mackenzie Delta contributed to the poor success of sumps in that area. In contrast, the higher success rate of sumps in the Parsons Lake region were associated with good site drainage and colder permafrost temperatures.

Based on review of literature pertinent to sump construction in continuous permafrost, assessment of abandoned drilling sumps and abandonment practices, the following recommendations are made:

1. Minimize disturbance to terrain adjacent to drilling sumps in order to ensure long-term sump success.
2. Remediate long-term subsidence of the sump cap to ensure containment of drilling wastes.
3. A lack of adequate backfill will result in a poorly capped sump, which can increase the chances of seepage of drilling fluids.
4. Consider the effect of snow accumulation on ground thermal conditions in the context of long-term sump stability.
5. Consider ground thermal conditions when assessing feasibility of permafrost as a medium for permanent containment of drilling wastes.
6. Consider several factors associated with alluvial environments when evaluating the feasibility of sump construction in the Mackenzie Delta.
7. Consider alternative options for disposal of camp wastes.
8. Re-evaluate the length of time for which a project proponent be responsible for a waste sump.
9. Develop a monitoring program to evaluate the thermal and geochemical evolution of sumps in different environments within the study region.
10. Consider the potential effect of climate change on the efficacy of permafrost as a medium for containment of drilling fluids.

1.0 Introduction

Oil and gas exploration in the Canadian western Arctic has relied on permafrost as a containment medium for permanent disposal of drilling fluids (French, 1978). Drill cuttings and drill fluids are disposed of in sumps which are usually excavated adjacent to the well-head. Sumps are later back-filled with the excavated material once the contents are partially or completely frozen. The intent is that permafrost will aggrade into the back-filled materials and that the sump cap will contain the active layer thus maintaining waste within underlying permafrost (Figure 1).

The effectiveness of permafrost to permanently contain drilling fluids is influenced by the construction, site operations and abandonment practices of industry (French, 1980). In addition, the physical characteristics (ice-content) of permafrost can affect site sensitivity and quality of backfill, and the ground thermal conditions can influence freeze-back of the sump and the effectiveness of permafrost to immobilize drilling wastes (French, 1978). It is critical that the long-term effectiveness of sumps in the Mackenzie Delta region be evaluated to guide appropriate practices for the future, as sumps are being considered as the primary disposal option for drilling muds produced during contemporary exploratory drilling operations in the Mackenzie Delta region.

Renewed hydrocarbon exploration in the north has stimulated the Water Resources Division of the Department of Indian Affairs and Northern Development to review sump design, construction and abandonment procedures, and to assess a small number of the approximately 250 drilling and camp sumps that have been constructed in the Mackenzie Delta region. The purpose of this report is to provide a review of literature relevant to the use of sumps in areas of continuous permafrost and to evaluate the

performance of sumps constructed in the 1970's. An overview of the physical environment in the Mackenzie Delta region and historical site inspection records provide the context within which to interpret the success or failure of the abandoned wellsites. Inventories based on photographs and field notes were compiled for a total of 24 sumps in the Mackenzie Delta, on Richards Island and in the vicinity of Parsons Lake. This investigation highlights long-term implications of abandonment practices and sump design, and investigates the influence of regional environmental conditions on sump integrity. Recommendations to help guide government regulators with respect to sump construction in the Mackenzie Delta region are provided.

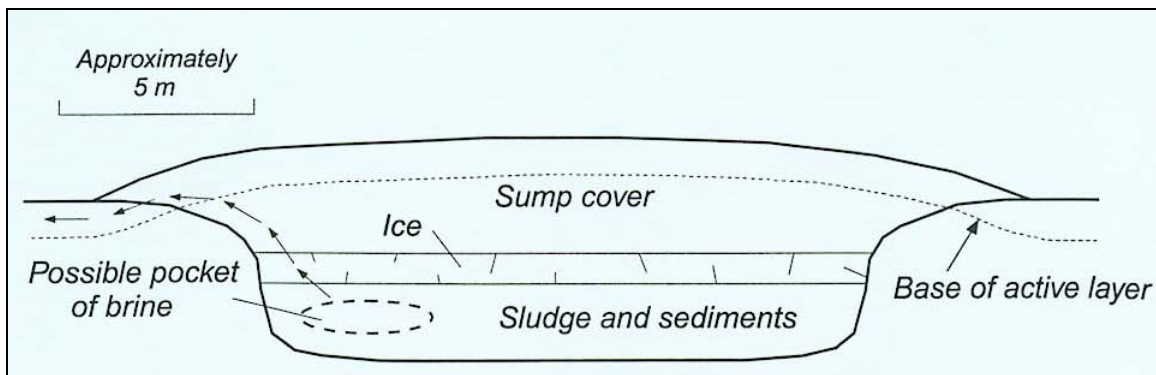


Figure 1. Schematic cross-section of a drilling mud sump. Sludge consisting of cuttings and drilling fluids is encouraged to freeze partially or fully. Material saved from the excavation is then used to cap the sump. If the sludge is not completely frozen, seepage upwards due to subsidence of the cover may occur. This seepage can move into the active layer and travel outwards from the sump (Dyke 2001, Figure 1).

2.0 Sump Construction and Guidelines

The following section provides a brief overview of location, construction, operating and abandonment guidelines for sumps in continuous permafrost. The composition of drilling fluids is also considered.

2.1 Guidelines for Locating Sumps

Guidelines specify that the project proponent must obtain necessary permits and demonstrate that the location of the site is appropriate prior to beginning construction (Spencer Env.,1987). Terrain and permafrost conditions must be considered, specifically, sites underlain by high ground ice contents should be avoided. Siting within a drainage feature, downhill of a perennial snowbank and side-hill locations are discouraged. Drilling fluid sumps should be located a minimum of 100 m from the ordinary high water mark of any permanent water body or stream. The sump should not be constructed close to ephemeral drainage, or locations with high water tables, springs and groundwater seepage (Spencer Env., 1987). Appropriate terrain is flat or gently sloping and topographic highs which promote surface drainage are favourable (Spencer Env., 1987). These guidelines imply that proper site selection requires pre-inspection of the proposed site during the snowfree period involving a comprehensive assessment of terrain, hydrologic and permafrost conditions. Aboriginal peoples hunt and trap throughout many regions rich in hydrocarbon reserves such as the western Arctic coast, therefore traditional land use should also be considered during site selection.

2.2 Construction Guidelines

Sump construction can be initiated once the contouring of the wellsite area has been completed. The locations of the sump and the spoil pile should be flagged prior to activating heavy equipment and the area should be cleared of snow to prevent incorporation of snow and ice in the backfill (Spencer Env., 1987). Sumps are generally constructed by drilling and blasting, followed by ripping and excavation using a dozer or excavator.

The volumes of drilling waste generated during drilling operations can be large. Hardy and Stanley, (1988) suggest that a sump should have a working volume between 0.78 and 1.3 m³ for every meter of hole drilled. The following considerations should be taken into account when estimating the size requirements of sumps: a) Expected duration of the drilling program; b) possible adjustments to the target depth; c) an extended drilling season; d) the nature of geological formations that will be drilled through, the presence of permafrost; e) the blowing in of snow; and e) the inflow of groundwater (Spencer Env., 1987). However, recent advancements in drill rig technology, recirculation of drilling fluids and drill/cutting separation could significantly reduce the volume of wastes and the size of future sumps.

2.3 Drilling Fluids

The purpose of drill fluids is to transport cuttings to the annulus, to cool and clean the drilling bit, to reduce friction, to provide borehole stability, to prevent inflow of groundwater or hydrocarbons into the hole and to seal pores and openings in formations that are being drilled (Piteau Engineering Ltd., 1988). In the north, brine-based drilling

fluids have been used most extensively and are appropriate for wells deeper than those where freshwater-based systems can be used. Oil-based fluids are rarely used in the north because disposal of oil-based fluids and coated drill cuttings has generally been prohibited. Typically, the constituents of brine-based mud are potassium chloride, bentonite, cellulose polymers, lignosulphonates and sodium hydroxide (Piteau Engineering Ltd., 1988). Saline water allows for circulation of a colder drilling fluid, which will help to reduce the thermal degradation of permafrost. Bentonite is used as a viscosifier, to increase mud density, promote hole stability and reduce infiltration losses.

2.4 Operation Guidelines

Sump contents should consist of only drilling fluids and cuttings, and the quantity and types of mud used, including additives at the wellsite should be recorded (Piteau Engineering Ltd., 1988). Smith and James (1979) recommended that waste discharged into the sump should be sampled at regular intervals. If the quantity of fluids exceeds the amount that was anticipated, regulatory officials should be consulted on measures to deal with this excess fluid. French (1978) and Smith and James, (1979) discourage the extension of existing sumps during the summer period. Drilling fluids should be maintained a minimum of 1.2 m below the level of the adjacent ground surface to keep fluids beneath the permafrost table (Spencer Env., 1987). However, at undisturbed sites in the Mackenzie Delta, active layer depths commonly exceed 1.2 m (Gill, 1972), thus acceptable freeboard should be at least 2 m.

2.5 Abandonment Guidelines

Sump reclamation involves capping the sump with backfilled material, aggradation of permafrost into the sumped materials and containment of the active layer within the sump cap so that the drilling fluids remain immobilized in the frozen ground (Figure 1). To ensure proper drainage and that the active layer is maintained above the level of the drilling fluids, a cap of well-compacted material at least 1.5 m in height and overlapping sump edges should be placed over top (Spencer Env., 1987). Furthermore, backfilling should occur only when the sump contents have completely frozen to avoid the upward displacement of drill fluids (French, 1978). Smith and James (1979) indicate that revegetation of the sump should be encouraged. The problems associated with sumps and site reclamation are considered in the following report.

3.0 Review of Literature

3.1 Solute Redistribution during Soil Freezing

Disposal of wastes in regions underlain by continuous permafrost has relied on the assumption that frozen sediments are impermeable and that perennially frozen ground will store wastes indefinitely. However, frozen sediments have a measurable permeability, which increases with temperature (Burt and Williams, 1974). Furthermore, salinity can affect the freezing point of water, so that the unfrozen water content and permeability of a frozen soil may remain high at temperatures below 0°C.

It is also known that during the freezing of fine-grained sediments, water and solutes migrate together along a thermal gradient (Cary and Mayland, 1972; Qui *et al.*, 1988). In contrast, during the freezing of coarse-grained silty sands, unfrozen water is pushed out of soil pore spaces into the adjacent unfrozen soil to accommodate expansion during phase change from water to ice. This process is termed pore-water expulsion and has been observed as permafrost aggrades into sediments of drained lakes in the Mackenzie Delta region (Mackay, 1997). The expulsion of pore-water is accompanied by rejection of salts from the ice phase during nucleation of ice crystals. Therefore, in a closed freezing system such as a sump, pore-water solute concentrations in the unfrozen zone may increase as the permafrost aggrades into the adjacent sediments. The resultant solute enrichment of the unfrozen zone can inhibit ice-nucleation and ice-bonding of these sediments despite penetration of the 0°C isotherm (aggradation of permafrost) (Mackay, 1997).

The physical and chemical behaviour of pore-water during freezing is directly relevant to assessing the effectiveness of permafrost in containing saline drill fluids. For

example, in warm permafrost (above -5°C), muds with a potassium chloride (KCl) concentration of 10% would partially melt and be available for expulsion from the sump or seepage into the surrounding sediments via the active layer during the warmest time of the year (Dyke, 2001). Maximum annual permafrost temperatures and the depths to which these temperatures extend vary throughout the study area depending on the thermal regime at the particular site.

In the past, drilling muds were sometimes diluted to promote ice-bonding of sump fluids. However, a greater amount of energy is required to freeze soils with a high water content, thus retarding penetration of the 0°C isotherm. Furthermore, solutes can reconcentrate during freeze-back and subsequent annual cooling cycles. The extent to which solutes are reconcentrated is dependant on the rate of freezing, the pore-water salt concentrations, the nature of the substrate and the temperatures within the sump. There are no studies that have investigated this process in the context of sumps even though redistribution of salts within a sump can affect its long-term stability.

3.2 Sump Studies in the Zone of Continuous Permafrost

In the 1970's and 1980's, several reports were published through the Arctic Land Use Research Program (ALUR), Environmental Studies Division of the Northern Protection Branch (DIAND). For example, French, (1978), and French and Smith, (1980) focused on terrain and permafrost issues associated with sump construction in continuous permafrost areas while studies by Smith and James, (1979, 1985) investigated the ecological impacts.

French (1978; 1980) investigated over 60 wellsites in the Canadian Arctic and found more than 25% of wellsites displayed problems of varying magnitudes. French (1980)

indicated that site conditions and the timing and nature of drilling operations were key factors in explaining the observed problems that were summarized into the following three groups:

1. Non-containment problems were related to inappropriate capacity of the drill sumps. Remedial measures included construction of additional sumps, modification of the initial sump or establishment of remote sumps. Modification to the initial sump, however, could result in significant disturbance and this practice was discouraged.
2. Melt-out problems during summer operations occurred because warm fluids and summer air temperatures promoted thaw of ice-rich permafrost adjacent to the sump, causing slumping of the sump walls and enlargement of the sump. Melt out of ice-wedges transecting the sump walls caused drill fluids to escape into the environment. This problem was acute where sumps were constructed on slopes. The magnitude of melt-out problems was related to the air and ground temperatures at the site and ice content of the surrounding permafrost.
3. Issues related to sump abandonment and restoration were the most commonly encountered problems. If the sump was back-filled prior to complete freeze-back, the weight of the overburden sometimes caused drill fluids to squeeze to the surface of the sump. Frequently, sumps were waterlogged and slumped because of the melt-out of ice and snow within the backfill. Thawing of ice-rich backfill could cause subsidence of the sump cap and accumulation of water in the depressions, producing a “heat-sink” that could thaw the unfrozen or semi-frozen sump fluids buried beneath. Subsurface leakage of fluids occurred if the sump walls thawed or if the

sump was too full when capped. Finally, excessive terrain disturbance adjacent to sumps initiated degradation of near-surface ice-rich permafrost causing subsidence and ponding of water adjacent to the sump.

The greatest amount and most severe problems were related to two-season and summer drilling programs because the summer temperatures and warm drill fluids often thawed adjacent permafrost causing melt-out problems (French, 1980). Furthermore, drill fluids would not always freeze-back completely before the sump was capped the following winter. The fewest problems were encountered during single-season winter programs because drill fluids froze quickly upon entering the sump and damage to surrounding terrain was minimal.

French and Smith (1980) instrumented a sump in cold permafrost on Cameron Island in the High Arctic. In the two-season operations in which sump fluids thawed during summer, temperatures at a depth of 1 m below the sump floor rose from -8°C to -4°C . Over the following summer, the temperatures increased more slowly to a quasi-equilibrium of about -1°C to -2°C . French and Smith (1980) concluded that in areas of warmer permafrost temperatures, the geothermal disturbance created by an influx of sump fluids during a summer operation could be sufficient to induce thermal degradation of the sump floor.

Several studies by Smith and James (1979, 1985) focused primarily on the ecological effects of drill sumps in the Arctic. Issues pertaining to toxicity of sump fluids are not addressed here, however, their general recommendations suggested continued use of sumps for containment of drilling waste in the High Arctic. Major problems with non-containment of drilling fluids were associated with poor sump location, drilling difficulties

and poor sump rehabilitation. They suggested locating sumps in hollows to prevent the spread of contaminants by downslope water movement. The mixing of overburden with frozen sump fluids during expansion of existing sumps was discouraged as it sometimes resulted in contamination of active layer soils. The importance of minimizing disturbance to the surrounding terrain during drilling was also recognized (Smith and James, 1985).

In 1988, the Environmental Studies Research Fund 093 – Handling and Disposal of Waste Drilling Fluids from On-Land Sumps in the Northwest Territories and Yukon was prepared (Hardy and Stanley, 1988). This summarized drilling fluid disposal and sump construction and abandonment procedures for northern environments and consisted of two reports prepared by Stanley Associates Engineering Ltd. (1987) and Hardy (1987). The synthesis of these reports (Hardy and Stanley, 1988) was intended to guide future initiatives in the improvement of drilling fluid disposal practices.

However, with the exception of the ALUR studies in the 1970's and early 1980's, few field-based studies pertaining to sumps have been conducted. White (1999, 2000) inventoried several abandoned wellsites on Melville Island, the Mackenzie Delta region and the Mackenzie Valley. At several sites, active layer depths and ground temperatures were reported in addition to soil physical and chemical properties. The collapse and subsidence of many sump caps were reported in the Mackenzie Delta region. Local contamination was detected at the sites, but the cause of sump failure was not discussed.

In summer 2000, GeoNorth assessed several sumps in the Mackenzie Delta region to develop a methodology for qualitative field assessment of abandoned drilling wells so that a comprehensive, systematic survey of sumps in the region could be conducted (Geonorth, 2000).

The movement of contaminants in frozen soils has been studied at several sump sites in the Mackenzie Delta region (Dyke, 2001). Potassium chloride (KCl) has moved up to 50 m laterally from the sump edges within the level alluvial silts of the Mackenzie Delta and on surrounding tundra uplands. At sites in hilly terrain, KCl has moved up to several hundred meters downslope within the active layer. Dyke (2001) demonstrated that density-driven solute movement and thawing ice fabric of active layer soils promotes lateral movement of solutes through the active layer. He concluded that these processes and the presence of a frost table could widen the area potentially affected by contaminant migration from abandoned waste sites in permafrost areas.

Although some field research in the 1970's and early 1980's provided guidance to industry and regulators regarding the construction of effective sumps, the long-term integrity of these sites has not been evaluated. This report describes the status of sumps at several abandoned wellsites in the Mackenzie Delta region.

4.0 Study Area

Environmental conditions in the Mackenzie Delta area are reviewed to provide a context within which to interpret the data on success or failure of sumps in this region.

4.1 Surficial Materials, Permafrost and Geomorphology

Surficial materials, geomorphic processes, permafrost temperatures and ground-ice conditions vary between physiographic regions in the Mackenzie Delta area. The modern Mackenzie Delta (Figure 2) consists of silty alluvium deposited by floodwaters of the Mackenzie River. This is a dynamic environment of active erosion and deposition, characterized by shifting channels and thousands of lakes which are at different stages of expansion, drainage and infilling (Mackay, 1963). In the Delta, permafrost is considered to be discontinuous due to the thermal influence of the large number of water bodies (Smith, 1976).

If a fresh water body is deeper than the maximum thickness of winter ice, the underlying sediments will have a mean annual temperature above 0°C (Mackay, 1963). Therefore, unfrozen zones, known as taliks, are usually associated with lakes with greater than about 2 m depth. As stream channels shift laterally or lakes expand due to thermokarst processes, so too does the underlying talik. As a river channel migrates, permafrost on the cut bank side of the channel degrades and a point bar is deposited on the slip-off slope (Figure 3). Permafrost is eventually re-established on the aggrading slip-off slope with thickness increasing with distance away from the migrating channel, as the degree of thermal recovery increases with increased age of the land surface (Smith, 1976). The rate of permafrost aggradation at any particular location in the Delta is

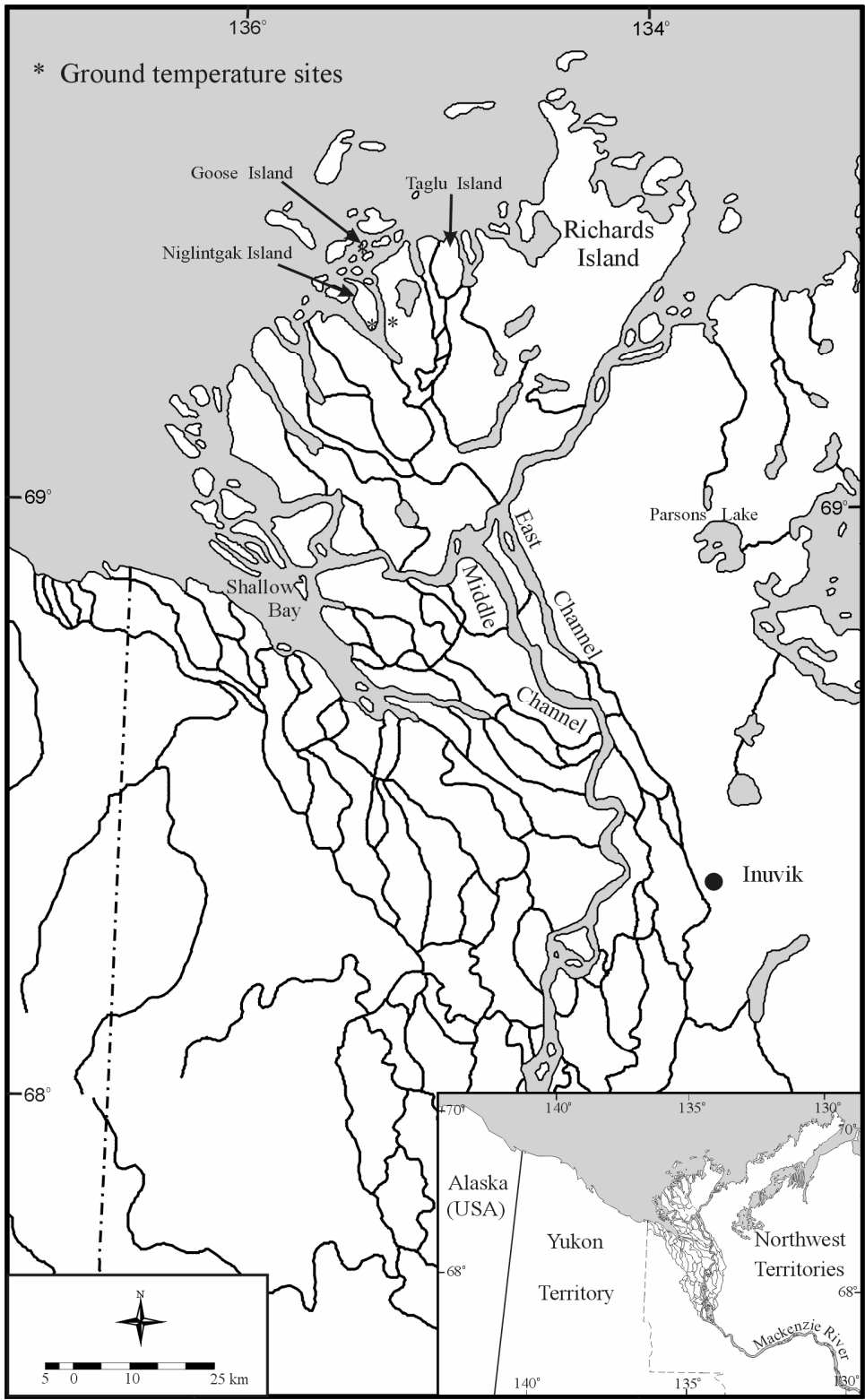


Figure 2. The Mackenzie Delta region.

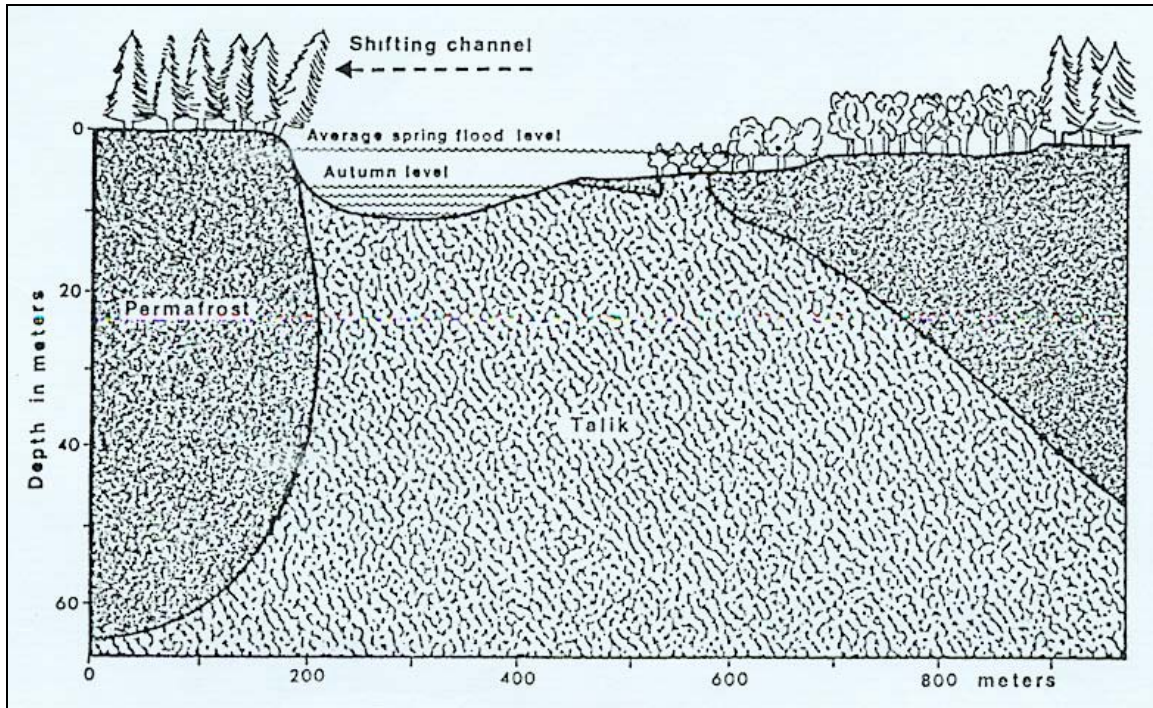


Figure 3. Diagrammatic cross-section showing permafrost configuration, shifting channel in Mackenzie Delta (Smith, 1975, Figure 4).

dependent on its proximity to water bodies (Smith, 1976) and on the stage of vegetation succession and winter snow accumulation (Smith, 1975).

Several sites were assessed in the Tununuk Low Hills, a physiographic sub-unit of the Tuktoyaktuk Coastlands (Rampton, 1988) (Figure 2). This surficial unit covers most of western Richards Island and parts of the Big Lake Delta Plain (Rampton, 1988). The topography is rolling with variable sedimentary units ranging from fine-grained till to glaciofluvial gravel. The materials are ice-rich with massive ice underlying much of the ground. The geomorphic features of this region (e.g., pingos, ground ice slumps, thermokarst lakes, patterned ground, oriented lakes) can be attributed to permafrost, high ice content of sediments and thermokarst processes (Rampton, 1988). The profile of ground ice is likely best estimated from data such as that presented by Pollard and French (1980, Figure 2). Permafrost thickness in Tununuk Low Hills is much greater than in the Mackenzie Delta, with maximum depths of about 700 m measured on northern Richards Island (Taylor *et al.*, 1996). Numerous lakes are inset into the terrain, and many are underlain by talik.

Surficial materials in the Parsons Lake region consist of coarse-grained glacial and glaciofluvial deposits (GSC, 1998). In some locations, steep-sided hills mark the location of ice-contact moraines. South of Parsons Lake lie glacial-lacustrine and lacustrine deposits, with peatlands in lower-lying hollows. Ground ice consists of some massive ice deposits, ice wedges and near-surface aggradational ice (Rampton, 1988). Polygonal networks associated with ice wedges are present throughout much of the area.

4.2 Climate and Permafrost Temperatures

The regional climate is characterized by long, cold winters. The monthly mean temperature from October to May is below 0°C. A steep summer temperature gradient exists between the coast of Richards Island and Inuvik. Colder summer temperatures at the coast and some distance inland are attributed to onshore winds blowing from the persistent ice cover of the Beaufort Sea (Burn, 1997).

While Inuvik receives about 175 cm of snowfall annually, less than 70 cm of snow falls in Tuktoyaktuk (Environment Canada, 1993). At tundra sites north of the treeline, snow is redistributed by winter winds, blowing free from exposed surfaces and accumulating in slope hollows and vegetation (Mackay and MacKay, 1974). Higher shrub vegetation on the south end of Richards Island and south towards Inuvik raises mean annual ground temperatures due to the trapping of snow. The effect of snowcover on ground thermal conditions is well documented in the Mackenzie Delta where deep snowbanks associated with willow stands result in thicker active layer depths (>1 m) and in some cases, talik development (Smith, 1975).

Permafrost thickness on Richards Island is over 500 m while permafrost underlying terrain adjacent to the Delta near Inuvik is about 300 m thick (Taylor and Judge, 1977). An interaction between climate and winter snowcover affect ground temperatures between the coast and Inuvik. Near-surface mean annual ground temperatures measured on the northern part of Richards Island are between -9°C to -10°C, compared to -3°C to -4°C on mainland near Inuvik (Rampton, 1988). In the Mackenzie Delta, numerous lakes and shifting channels, and deeper snow accumulation raise ground temperatures to between -2°C and -4°C (Mackay, 1963). Permafrost thickness in the Delta is less than 100 m, due to the thermal influence of water bodies.

5.0 Methods

The integrity of sumps constructed in the 1970's was assessed at 24 abandoned wellsites in the Mackenzie Delta region. A total of 24 drilling sumps and 23 camp sumps were described (Appendix 1) using recent photographs and site descriptions made by GeoNorth, 2000 and White, 2000. Environment Canada, Environment and Protection and Canadian Wildlife Services also contributed contemporary photo imagery for many of these sites.

Site identification, location, and regional setting were recorded. The degree to which the sump cap had subsided and the extent of surface water ponding was estimated from the photos and field notes. Drill and camp sumps were grouped as intact, subsiding, collapsing or collapsed. An elevated cap and absence of ponded water characterized an intact sump, whereas water accumulation in depressions on the sump cap indicated subsidence. The proportion of the cap covered by surface water was estimated. Subsidence was considered to be minor if ponding covered less than 15% of the sump cap. Active slumping of the sump cap into an adjacent pond was considered to represent a "collapsing sump". At some sites the sump cap had completely collapsed leaving only a geometrically shaped pond.

The extent of permafrost disturbance to terrain adjacent to the sumps was evaluated based upon local subsidence of the ground surface, ponding of surface water and degradation of ice-wedges. The nature of vegetation cover was also recorded as it could indicate contamination from degrading drilling sumps.

Site inspection reports were obtained from the DIAND District Office in Inuvik, courtesy of the District Manager. The year of operation, duration and time of abandonment were recorded. Inspectors' notes were reviewed to determine whether any problems were identified during operation or abandonment of the specific sites.

6.0 Results

Eleven of the wellsites examined were on alluvial sediments of the Mackenzie Delta, four were in the Tununuk Low Hills of western Richards Island and nine were in the vicinity of Parsons Lake (Figure 2). All of the sumps analyzed were constructed between 1972 and 1977. Seventeen of the sumps remained open for at least one summer season and seven were opened and capped during a single winter (Table 1).

6.1 Drilling Sumps

With respect to drill sumps, eight of 24 sumps investigated had totally collapsed (Table 1). These sumps were characterized by ponded water that covered at least the original area of the sump (Figure 4). Often, dead willows and salt efflorescences were observed around the ponds (Figure 5). Water depth was not measured, however several ponds were sufficiently deep that the bottom could not be seen. Six of the eight collapsed sumps were situated in alluvial sediments of the Mackenzie Delta.

Photographs and field notes indicated that four of the 24 sumps were degrading into adjacent ponds (Table 1). The sides of these sumps were actively collapsing and willow trees that formerly grew on the sump cap were often seen submerged in the expanding pond (Figure 6). The depth of ponded water adjacent to the sump caps was not measured but notes indicate that depths exceeded 1 m. Flocculated mud was also observed in some of the ponds adjacent to the degrading sump caps. Three of the four collapsing sumps were in alluvial sediments of the Mackenzie Delta.

Table 1. Summary of drill and camp sumps assessed in the Mackenzie Delta region. A total of 24 drill sumps and 23 camp sumps were assessed.

	<i>Number of Drilling Sumps</i>	<i>Percentage of Sumps</i>
Sumps open for Summer Drilling Operations	17	71
Sumps open for Winter Drilling Operations	7	29

<i>Mackenzie Delta Region Totals</i>	Number of Drill Sumps	Percentage of Drill Sumps	Number of Camp Sumps	Percentage of Camp Sumps	Geological Distinctions
Total Collapse	8	33	15	65	6 of 8 collapsed drill sites are in the Delta
Collapsing	4	17	0	0	3 of 4 collapsing drill sites are in the Delta
Subsidence	5	21	3	13	
Minor Subsidence	2	8	1	4	
Intact	5	21	4	17	4 of 5 intact sumps are in the Parsons Lake area
Problem Sumps (according to DIAND)	17	71	0	0	

Note: “Total collapse” and “collapsing” are criteria for failure because sump fluids are no longer maintained in permafrost. “Subsidence” suggests thermal degradation of underlying permafrost and there is a high probability that all of the fluids are no longer immobilized in permafrost.



Figure 4. Collapsed sump (Shell Kugpik L-24) near Reindeer Channel, Mackenzie Delta. Photograph: Summer 2000.



Figure 5. Salt efflorescences and dead vegetation around the sump perimeter in Mackenzie Delta (Shell Kugpik O-13) indicate contamination of surrounding terrain. Contaminants are slowly flushed from these sites by floodwaters of the Mackenzie River. Photograph: Summer 2000.



Figure 6. Sump cap actively slumping into pond (Gulf Mobil Toapolok O-54), Mackenzie Delta. Live willows in pond suggest that recent expansion of the pond was rapid. Photograph: Summer 2000.

Subsidence and accumulation of surface water was observed on the caps of five of the 24 drill sumps (Table 1, Figure 7a). Close up inspection of the pond indicates that willows were submerged in the standing water (Figure 7b). Because willows tend not to grow in deep standing water their current growth position suggests their establishment prior to subsidence, indicating that the sump cap was stable for several years prior to subsiding (Figure 7b).

Very minor subsidence was detected at two sites and a total of five sites were considered to be intact (Table 1). Four of the “intact” sumps were in the Parsons Lake area (Figure 8). Intact sumps tended to be well-drained and surface disturbance to the surrounding terrain was minimal (Figure 8). Only one of the eleven drill sumps assessed in the Mackenzie Delta was considered to be intact, however there was ponding around the periphery of the sump. Driftwood on the sides and top of the sump indicated that it flooded regularly (Figure 9).

6.2 Camp sumps

Fifteen out of 23 camp sumps examined in this study had totally collapsed (Table 1). These sumps were characterized by small, but deep rectangular pools (Figure 10). Despite their poor performance, terrain surrounding the camp sumps showed less evidence of disturbance than was observed around the drill sumps. Occasionally, camp debris was observed in the ponded camp sumps. Willows that had grown on top of the camp sumps were sometimes drowned in the sump ponds suggesting that subsidence and collapse had followed a period of relative stability. Vegetation growth around the collapsed camp sumps was usually vigorous. Three camp sumps showed subsidence and another one showed minor subsidence (Table 1). A total of four camp sumps were intact, three of which were at abandoned wellsites in uplands to the east of the Mackenzie Delta, in the Parsons Lake area.



Figure 7a. Subsidence and ponding on sump cap, (Gulf Mobil Siku C-11) Parsons Lake area. The standing water has accumulated due to subsidence of the sump cap. Photograph: Summer 2000.



Figure 7b. Close-up of the ponded area with drowned willows. Photograph: Summer 2000.



Figure 8. An intact sump (Gulf Mobil Ogeoqueoq J-06) in the Parsons Lake area. Note that the sump cap is largely unvegetated and that the site is well-drained. Photograph: Summer 2000.



Figure 9. Sump cap at the Kumak site in outer Mackenzie Delta is in relatively good condition, however there is considerable ponding around the periphery of the sump. Note driftwood on the sump cap.



Figure 10. A collapsed camp sump adjacent to a well-capped, intact drill sump (Gulf Mobil Parsons P-53), Parsons Lake region. Photograph: Summer 2000.

6.3 Department of Indian Affairs and Northern Development Inspection reports

DIAND Land Inspectors made regular site visits during the establishment, operation and abandonment of the wellsites. Files regarding the respective sites were thorough and well organized. Most all files pertaining to sites considered in this report had been closed within five years of site abandonment with the exception of Parsons Lake D-20. Within the Delta region, major problems identified by the inspectors with respect to individual sumps included flooding in spring and fall by Mackenzie River water, insufficient capping materials and excessive site disturbance during drilling (Appendix 1). At upland sites in the vicinity of Parsons Lake, major problems included failure of sump caps because contents were not frozen, volume issues where the sump was not large enough to accommodate the drilling fluids and the meltout of ice lenses and escape of drill fluids downslope. At sites on Richard's Island, meltout problems during summer operations and poor site location with respect to local drainage were noted.

7.0 Interpretation and Discussion

7.1 Drilling sumps

French (1978, 1980) indicated that the greatest number of terrain problems associated with sump construction and abandonment were encountered during summer operations, while single-season winter operations yielded relatively few problems. In this study, no clear trends were identified between the timing of operation and the long-term success or failure of drilling sumps in the Mackenzie Delta region, although some patterns may have emerged with a larger sample population.

A morphological assessment of the drilling sumps and their surrounding terrain indicated that only 21% of the sumps abandoned in the 1970's were intact with no indication of subsidence or failure (Table 1). Only two of the five intact sumps were single-season winter operations. One intact sump in the outer Mackenzie Delta was open throughout the summer season. DIAND inspectors noted that backfilling had taken place prior to complete freeze-back of sump fluids in March, but commented on the abundance of fill and the large cap. To date, the sump cap is in reasonably good shape despite the fact that the site floods occasionally as evidenced by driftwood on the sump cap (Figure 9). Considerable ponding around the perimeter of the sump will probably lead to its degradation at some time in the future.

Minor problems were observed during abandonment of the four intact drill sumps in the vicinity of Parsons Lake, but overall, capping and abandonment were satisfactory to the DIAND inspectors. Notably, 80% of the intact sites (4 out of 5) were in this region.

A large cap and the coarser nature of the backfill characterized many abandoned sumps in the Parsons Lake area (Figure 10). These characteristics may reflect the availability of granular materials in the region. The intact sumps were situated on slopes and on well-drained hilltops. Exposed positions on positive relief features discouraged ponding of surface water which could contribute to thermal degradation of the sump and its eventual collapse. Furthermore, their exposed situation inhibited winter snow accumulation, promoting freeze-back of sump fluids and maintenance of cold ground temperatures. However, failure would result in rapid downslope leaching of toxic fluids (Smith and James, 1979; French, 1980).

About 30% of the sump caps had subsided sufficiently to promote accumulation of standing water on the sump cap or around the sump perimeter (Table 1). Although subsidence and ponding do not indicate that the sump has failed, ponded water represents a heat sink that can promote further degradation of underlying permafrost. In turn, degradation of permafrost can enlarge the pond and increase the magnitude of the thermal disturbance.

Subsidence of the sump cap may be initiated in the summer immediately following abandonment if the capping materials are ice-rich or excessive amounts of snow were incorporated into the fill (French, 1980). DIAND inspectors noted the subsidence of sump caps following abandonment and where subsidence was severe, further remediation was enforced. More than two decades later, these sumps have nevertheless subsided to varying degrees.

Field evidence suggests that some of the subsidence of sump caps was gradual, and that some severe subsidence has occurred in recent years. This interpretation is

based on the presence of submerged willows in ponded-water in and around several sump caps (Figures 7a and 7b). The situation of these trees implies that the sump caps must have been stable for several years prior to subsidence and collapse. Dyke (2001) points out that the thermal environment of a sump may change as willows establish on the tops of sumps resulting in an increased winter snow accumulation. The willows trap snow, warm ground temperatures and even degrade underlying permafrost as documented on point bar environments of the Mackenzie Delta (Smith, 1975).

Almost 50% of the drill sumps assessed in the Mackenzie Delta region were in the process of collapsing or had completely collapsed. Total collapse, indicated by the absence of any visible sump cap and presence of a geometric pond indicated degradation of permafrost within the sump materials. Some pond depths certainly exceed maximum thickness of winter ice cover. Once water in the depressions is deep enough to raise the mean annual pond-bottom temperatures above 0°C, thawing beneath the pond is continuous. If the permafrost is ice-rich, the bottom of the pond will subside proportional to the ice content of the thawing sediments, causing the pond to deepen. Ponding adjacent to the sump will usually result in degradation of the sump.

DIAND inspectors noted several problems during the abandonment of sumps that are currently degrading or have already collapsed. However, issues such as overfilling the sumps and minor disturbance to surrounding terrain were raised by inspectors at sites that have degraded as well as those that have remained intact. A notable point involved disturbance to terrain surrounding the sump, which caused surface ponding and eventual collapse of several sumps in poorly-drained sites. Historical site photographs (French, 1978) indicate disturbance, subsidence and ponding on terrain surrounding sites

constructed in wet, low-lying tussocky terrain in the Taglu Island area of the Delta. During abandonment, the removal of active layer soils around the sump initiated a chain of events beginning with the active layer extending into previously frozen ground, thawing of near-surface ground ice, surface subsidence, ponding, expansion of the pond and of the extent of thermal disturbance. These factors have clearly led to degradation of several sumps in the Taglu Island area (Figures 11a & 11b).



Figure 11a. Sump cap collapsing into an adjacent thaw pond in the Taglu Island area, Mackenzie Delta. Photograph: Summer 2001.



Figure 11b. Overhead view of the sump in Figure 11a.

In the Mackenzie Delta, DIAND inspectors also reported problems associated with flooding of sumps during operation or immediately following capping. Flooding of an open sump can mobilize drill fluids and redistribute them into the local environment. Introduction of relatively warm river-water into the ground increases the magnitude of thermal disturbance, and promotes water accumulation in depressions that have developed as a result of disturbance during operation or abandonment.

Over 80% of the collapsed and collapsing sumps investigated in this study were in the Mackenzie Delta. Several factors may have contributed to the poor success of sumps in this region including construction and abandonment practices, which could be improved upon if the recommendations of French (1980) and Smith and James (1985) are followed carefully. However, there are inherent problems with constructing sumps in the Delta due to the dynamic geomorphic nature of the alluvial environment and as a result of the regional permafrost conditions. Regulators and industry must be cognizant of these issues, some of which are highlighted by data collected in this study.

As discussed in Section 4.2, permafrost in the Mackenzie Delta is warmer than on the surrounding tundra and its thickness is variable. Shifting channels, thermal effects of water bodies and deep snow cover associated with willow growth contribute to the warmer ground temperatures and thin permafrost. Temperature envelopes from sites in the outer Mackenzie Delta on and near Niglintgak Island indicate the range of permafrost temperatures that are encountered in this region (Figure 12). Permafrost on an alluvial island at the coast was between -5 and -8°C (Figure 12c). At willow sites in alluvial sediments permafrost temperatures were around -2°C (Figures 12a and 12b). Warm

permafrost is more susceptible to thermal degradation upon construction of a sump and the addition of drilling fluids as less energy is required to thaw the underlying permafrost. Thus, similar sump practices will have a greater negative effect on a sump situated in warm permafrost than one located in colder permafrost. Warm permafrost can also retard freeze-back of sump fluids. In the Delta, seasonal temperature fluctuations can raise temperatures in the top 3 to 4 m of permafrost above -5°C . As a result, sump contents with a KCl concentration of 10% would partially melt and be available for expulsion from the sump or as seepage into the surrounding sediments during part of the year (Dyke, 2001). At sites where the permafrost is about -2°C it is unlikely that the saline drill fluids would become immobilized by permafrost. It should be recognized that potential climate warming could increase permafrost temperatures and in areas where the permafrost is close to 0°C , it may be eradicated completely.

On aggrading point bars, permafrost thickness may be only a few meters to tens of meters in thickness (Figure 3). Some failed attempts to build sumps in the Delta occurred when blasting and excavation revealed unfrozen soil at the base of the sump. If permafrost conditions (temperature and thickness) are not evaluated prior to site selection, there is the additional risk that a sump may be built where permafrost extends only a few meters below the base of the sump and persists at temperatures just below 0°C . Minimal thermal disturbance would rapidly thaw a thin layer of warm permafrost, forming a through-going talik. This would result in subsidence of the sump cap and escape of drilling fluids.

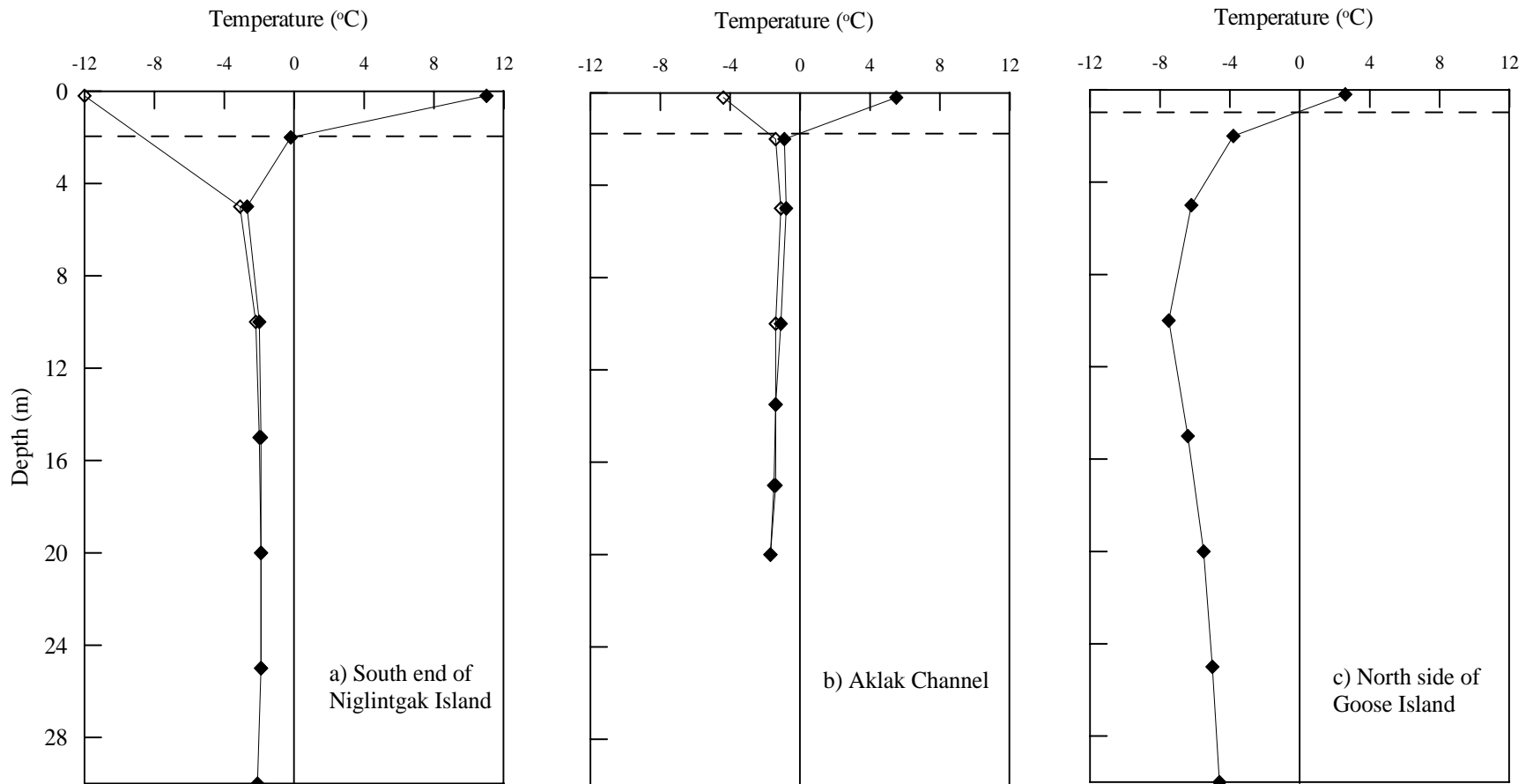


Figure 12. Ground temperatures from selected sites in outer Mackenzie Delta. Data was provided courtesy of L. Dyke, Geological Survey of Canada. For site locations see Figure 2.

Spring flooding of sump sites in the Mackenzie Delta also contributes to their poor success. Floodwaters eradicate winter snow cover and deliver heat into the frozen ground, accelerating active layer thaw. During flooding, fluvial processes may also contribute to the destruction of sump caps, particularly at coastal sites where wave action can erode the cap (Figure 9). Finally, Delta surfaces are characteristically poorly-drained and therefore depressions will accumulate standing water. Pondered water constitutes a heat sink that could initiate degradation of underlying permafrost. It should be pointed out that the base of the active layer at sedge meadow sites in the outer Delta is less than 50 cm above summer water levels, so that even summer storm surges can cause the water table to rise above that of the permafrost table causing saturation of the active layer. This affect can extend several tens of kilometers inland from the coast. Any active layer deepening and/or subsidence can drop the permafrost table to below the summer water level in the adjacent channel. Thus, surface ponding as a consequence of terrain disturbance is difficult if not impossible to avoid when constructing sumps in this terrain.

7.2 Camp sumps

Most of the camp sumps investigated in this study had collapsed (82%) (Table 1). Geometrically shaped ponds characterized the collapsed features. Only four out of 24 camp sumps were intact and three were at sites in the Parsons Lake region. The reason for the high failure rate of camp sumps is unclear. Surrounding terrain generally did not show marked signs of disturbance in comparison to terrain around drill sumps, and ponding, although extensive was almost always contained within the original area of the sump.

The success or failure of these sumps did not appear related to the timing of capping or duration of sump operations. Although speculative, failure was probably related to the warmth and volume of fluids released into the sumps. Based on poor success, encapsulation within permafrost did not appear to be an effective method of disposal for camp wastes in this region.

8.0 Recommendations

The study identified several factors that promote the failure of sumps. Although the relative importance of these factors is difficult to assess at present due to missing information on the construction, operation and abandonment phases, attention to these in the future will increase the success of sumps as a waste containment measure. The recommendations of this report are:

1. Minimize disturbance to terrain adjacent to drilling sumps in order to ensure long-term sump success. Excessive disturbance during drilling and abandonment can cause the active layer to deepen around the sump perimeter. This may allow drilling wastes to escape into the active layer and contaminate surrounding terrain. If the underlying permafrost is ice-rich, active layer deepening will cause the surface to subside, promoting accumulation of standing water. The standing water represents a heat sink that can lead to further degradation of surrounding permafrost and expansion of the pond. This process initiated the gradual degradation of several sumps in the Mackenzie Delta (Figure 6), where this problem was most common. In Parsons Lake area, subsidence and accumulation of standing water appeared to be less of a concern where most sites were well-drained.

French (1978) associated the collapse of the sump cap in years immediately following sump abandonment to the incorporation of snow and ice in the infilled materials. However, observations made in this study suggest that sump collapse can occur years and even decades after site abandonment. Ponding and settlement around sumps pose a threat to long-term stability even if the sump was well-capped and the initial aggradation of permafrost was successful. It should be noted that sumps

recently constructed in the Mackenzie Delta appear to be well-capped and disturbance to the surrounding terrain was minimal. Nevertheless, some ponding has been observed around the periphery of the sump caps (Figure 13) and could initiate thermal degradation of sumps in the future.

2. Remediate long-term subsidence of the sump cap to ensure containment of drilling wastes. Minor subsidence of the sump surfaces due to melt-out of ice-rich infill may appear to be of little consequence in years immediately following capping, however these depressions promote accumulation of standing water over the sump that can slowly lead to degradation of permafrost in the sump. The original permit holder should be obligated to maintain the site and mitigate against long-term degradation.
3. A lack of adequate backfill will result in a poorly capped sump, which can increase the chances of seepage of drilling fluids. If excavated material was ice-rich and operations extended through the summer, there would be a loss in the volume of backfill proportional to the ice content of the material, resulting in a shortage of fill upon abandonment. If the cap is not of sufficient thickness the base of the active layer may descend below the level of drilling fluids, allowing for contaminants to escape from the sump. Poorly overlapped edges can result in subsidence and ponding around the periphery of the sump, which can lead to thermal degradation of the sump cap and escape of drilling fluids. According to French (1978), capping problems are particularly acute where there is a lack of accessible aggregate.
4. Consider the effect of snow accumulation on ground thermal conditions in the context of long-term sump stability. Sump morphology or revegetation of the sump can promote the accumulation of snowdrifts, which insulate the ground and



Figure 13. Ponding of water around recently constructed sump (Kirk M-15), Mackenzie Delta.

warm permafrost temperatures. The growth of willows on the top of stable sump caps can promote snow accumulation, and affect the ground thermal regime. Snow accumulation around the perimeter of a sump may warm ground temperatures, increasing the active layer depths around the edges of the sump.

5. Consider ground thermal conditions when assessing feasibility of permafrost as a medium for permanent containment of drilling wastes. Warm permafrost is more susceptible to thermal degradation following excavation of a sump and addition of drilling fluids because less energy is required to thaw the surrounding permafrost. The potential effect of snow accumulation on the thermal regime of a sump would have much greater implications in areas where the permafrost is warm. The combination of warm permafrost temperatures and saline porewater can inhibit

freeze-back and ice-bonding of sump fluids. In such cases the drilling wastes will remain mobile despite aggradation of permafrost. Thus, similar construction and abandonment practices in warm and cold permafrost may yield different results with respect to immobilization of drilling wastes in frozen ground.

6. Consider several factors associated with alluvial environments when evaluating the feasibility of sump construction in the Mackenzie Delta. A) Permafrost ground temperatures in the Delta are warmer than on the coastal Islands (Figure 13) and the adjacent tundra. Warm ground temperatures inhibit freeze-back of sump fluids. Addition of drilling fluids to sumps excavated in warm permafrost during summer drilling operations may be sufficient to degrade permafrost at the base of the sump. B) Permafrost thickness is highly variable throughout the Delta. Construction of sumps in shallow permafrost could result in the complete degradation of underlying frozen ground, escape of sump fluids and subsidence of the sump cap. Permafrost thickness should be assessed prior to sump construction. C) Flooding of sumps can cause several problems. For example, flooding of open sumps redistributes drilling muds into the surrounding environment and introduces warm water to the sump increasing the magnitude of thermal disturbance. Once the sumps are capped, floodwater may accumulate in depressions around and on the sump cap. D) Fluvial erosion may slowly remove capping materials and channel migration can result in the complete destruction of a sump. Proposals suggesting the use of drilling sumps should demonstrate that the above mentioned issues are fully appreciated and that appropriate mitigative measures will be taken into account. If this is not the case, a similar success rate

(less than 50%) for sumps in the Delta should be anticipated. Figure 14 illustrates an intact sump in the Mackenzie Delta. Although this site was not included in our analysis, several aspects of its construction can be instructive. The site is not close to major channels and the terrain is relatively well-drained. Disturbance to surrounding terrain was negligible. The absence of logs washed up on the sides of the sump cap suggest that when this site does flood, the energy environment is low, therefore it is not likely that fluvial processes have undermined site stability. The site was not originally colonized by willows, indicating that the permafrost is neither warm nor thin. The site has revegetated but thus far, no negative effects of willow growth and enhanced snow accumulation are visible. The subtle relief of the sump cap may inhibit deep drifts from collecting around the perimeter of the sump, maintaining colder permafrost temperatures around the periphery of the sump and preventing active layer deepening and thaw settlement. Detailed investigation of site conditions, including ground temperatures, winter snow accumulation, active layer depths and construction and abandonment procedures could be contrasted with those at a degrading site. Such information would provide useful data to help guide appropriate procedure and site selection for future sump construction in the Delta.



Figure 14. Intact sump, sedge meadow, outer Mackenzie Delta.

7. Consider alternative options for disposal of camp wastes.
8. Re-evaluate the length of time for which a project proponent be responsible for a waste sump. The data indicates that degradation of a sump can occur several years after abandonment and therefore a proponent should maintain responsibility for the site after the sump is capped.
9. Develop a monitoring program to evaluate the thermal and geochemical evolution of sumps in different environments within the study region. The literature review indicates the paucity of temperature data from within sumps making it difficult to assess how thermal conditions evolve throughout the life of a sump or what conditions initiate thermal degradation and sump failure. A thermal monitoring program could investigate how factors such as surface ponding, revegetation and patterns of snow accumulation affect the thermal regime of a sump. Furthermore,

no process-related studies have investigated the redistribution of drilling fluids during freezeback of a sump. These data could assess the fate of contaminants during permafrost aggradation and determine the maximum permafrost temperatures that will immobilize drilling fluids.

10. Consider the potential effect of climate change on the efficacy of permafrost as a medium for containment of drilling fluids. Climate induced warming may increase the temperature of permafrost and could result in eradication of warm permafrost (Wright *et al.*, 2000). Active layer thickness may also increase causing surface subsidence at sites where permafrost is ice-rich.

9.0 Conclusions

The report assessed the long-term stability of several drilling and camp sumps in the Mackenzie Delta region. This study suggests that long-term stability of sumps was linked to abandonment procedure. However, several sites deemed stable by DIAND inspectors, built in general accordance to guidelines, (following recommendations put forth by French, 1978) have experienced questionable success in their ability to contain drilling muds.

Assessment of abandoned drilling sumps in the Mackenzie Delta region highlights the importance of minimizing disturbance to the surrounding terrain. Surface disturbance can promote water accumulation in and around sump caps and can lead to thermal degradation of the sump, irrespective of other factors regarding sump construction. Also, minor subsidence of some sump caps after several years of apparent stability has raised questions regarding the effects of revegetation, snow accumulation and modification of ground temperatures on long-term sump stability. If sumps are to be used in the future, their thermal evolution should be better understood.

It is important to note that environmental conditions (permafrost temperatures, ground ice characteristics, and hydrology) vary throughout the study region and clearly affect the success of sumps. For example, the success rate of sumps constructed in the Mackenzie Delta was very low. Although numerous factors may have contributed to their failure, warm permafrost temperatures, variable permafrost thickness and frequent flooding make sump construction and long-term containment of drilling muds in the Mackenzie Delta difficult. If construction of sumps in this region is permitted, regulators and industry must recognize the inherent risks. It is imperative that a monitoring strategy be developed to understand processes leading to their success or failure and to guide the

management of drilling wastes in the future. Based on a review of literature pertinent to sump construction in continuous permafrost, assessment of abandoned drilling sumps and abandonment practices the following recommendations were made:

1. Minimize disturbance to terrain adjacent to drilling sumps in order to ensure long-term sump success.
2. Remediate long-term subsidence of the sump cap to ensure containment of drilling wastes.
3. A lack of adequate backfill will result in a poorly capped sump, which can increase the chances of seepage of drilling fluids.
4. Consider the effect of snow accumulation on ground thermal conditions in the context of long-term sump stability.
5. Consider ground thermal conditions when assessing feasibility of permafrost as a medium for permanent containment of drilling wastes.
6. Consider several factors associated with alluvial environments when evaluating the feasibility of sump construction in the Mackenzie Delta.
7. Consider alternative options for disposal of camp wastes.
8. Re-evaluate the length of time for which a project proponent be responsible for a waste sump.
9. Develop a monitoring program to evaluate the thermal and geochemical evolution of sumps in different environments within the study region.
10. Consider the potential effect of climate change on the efficacy of permafrost as a medium for containment of drilling fluids.

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