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CONTAMINANT MOVEMENT IN FROST-AFFECTED SOILS

by

Brenda Adams, B.Sc (Honours), B.Ed

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirement for the degree of
Master of Arts

Department of Geography

Carleton University
Ottawa, Ontario

June 1998

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the Faculty of Graduate Studies
acceptance of the thesis

"CONTAMINANT MOVEMENT IN FROST-AFFECTED SOILS"

submitted by **Brenda Adams**, B.Sc(Honours), B.Ed
in partial fulfilment of the requirements for
the degree of Master of Arts

A handwritten signature in cursive script, appearing to read "M. J. Smith", written over a horizontal line.

Thesis Supervisor

A handwritten signature in cursive script, appearing to read "M. J. Smith", written over a horizontal line.

Chair, Department of Geography

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June, 1998

ABSTRACT

In Arctic regions, frost-affected soils are often used to contain wastes. Investigating the integrity of frost-affected soils to contain wastes is significant because it will help to determine if they are an effective containment material. This issue should also be addressed because: i) the Arctic is a unique remote environment which is relatively untouched, ii) high costs prevent removal of wastes from the Arctic, therefore most are disposed of on-site in barrels or within the local soil, and iii) predicted climate warming could change the present behaviour of frost-affected soils in the Arctic.

Field studies were conducted to examine if sump fluids have migrated over time within frost-affected soils, from two disposal sites (sumps) in the Mackenzie Delta. Results show that over the last 20 years, measurable amounts of sump fluids have moved, up to distances of 10m from the sumps, within the active layer.

Laboratory research investigated if the cryogenic structure of a frost-affected soil augments the diffusion of a soluble contaminant. Observations of the laboratory studies indicated that the number of freeze-thaw cycles and the location within the soil influenced diffusive transport.

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Chapter One

INTRODUCTION

1.1 Importance of Study

1.1.1 General

Contamination of the environment creates concern due to the potential detrimental effects on the physical properties of environment, ecosystem characteristics, and human health. In the Canadian Arctic, negative effects of contamination are significant for several reasons. It is a reasonably unspoiled natural environment and therefore has remained relatively unaffected by contamination. The Canadian Arctic is also a distinct and fragile ecosystem since organisms are involved in short food chains (Barrie *et al.*, 1992). Geographically, the Canadian Arctic is remote which means that local point source contamination produced from industrial projects is often disposed of on-site. The cost of shipping wastes to southerly locations is expensive and would make the cost of industrial projects within the Canadian Arctic economically unfeasible (Piteau Engineering Ltd., 1988). Therefore, contaminants produced within this fragile, remote environment are most often dealt with on-site by storage in barrels or by ground disposal using the natural soil as a containment material.

Gas exploration is one type of local industrial activity which has generated substantial volumes of liquid and solid wastes in the Canadian Arctic. The long history of oil and gas exploration in the Canadian Arctic began in 1924 at Norman Wells. For a long time organizational difficulties and high costs confined industrial activity to the southern portion of the Northwest Territories. With improvements in technology, drilling in the far north became more feasible, and exploratory drilling began in the Arctic Islands and Mackenzie Delta in the late 1960s and early 1970s (Piteau Engineering Ltd., 1988). Drilling-mud waste was produced in substantial amounts from exploratory drilling and was frequently discarded on-site in pits or sumps excavated in frozen ground. Upon completion of exploratory drilling projects, sumps were allowed to freeze-back naturally and were then encased by the original local material excavated from the pit.

1.1.2 Specific

An investigation of drilling-mud sumps in the Mackenzie Delta is valuable for several reasons. In the construction of sumps, liners were not used since it has been assumed that frozen soil is impermeable to contaminants (Winnicky, 1995). However, Hardy BBT Ltd. (1988) and McLean (1993) determined that seepage of sump fluids had occurred from several sumps in the Mackenzie Delta. The reasons for such leakage may be intricate; to date, no detailed examination has been conducted to assess the containment of sump fluids within sumps in permafrost.

Active fluvial processes, such as flooding, channel migration, and bar erosion and accretion, occur in the Mackenzie Delta. The potential exists for sumps to be eroded or breached due to these dynamic fluvial processes. Loss of sump fluids from Mackenzie Delta sumps could contaminate the local environment.

In addition to these more obvious issues, the nature of permafrost containment of wastes needs to be examined. Sump integrity assumes the presence of impermeable frozen soil. Previous investigations of the movement of aqueous and non-aqueous fluids in frozen soils has been restricted to laboratory-prepared homogeneous media (Dyke, 1996). In nature, frozen and frost-affected soils are heterogenous and therefore have varying physical properties which could allow movement of contaminants. Frozen soils contain unfrozen water down to temperatures a few degrees below 0°C which could provide an avenue for fluid movement. Furthermore, the presence of solutes increases the unfrozen water content of a soil (Hivon and Sego, 1990). Frozen and frost-affected soils can also develop a cryogenic structure which has been shown to increase the hydraulic conductivity of the thawed soil by several orders of magnitude (Chamberlain and Gow, 1978; Egginton and Dyke, 1990; Eigenbrod, 1996). These physical factors assume a particular interest and importance in the Mackenzie Delta region due to its warm mean annual ground temperatures around -2°C (Dyke, 1996). The potential exists for sediments to be permeable due to the presence of unfrozen water in the soils. Therefore, it cannot be assumed that

frozen and frost-affected soils of the Mackenzie Delta region are completely impermeable.

Furthermore, anticipated climate change associated with global warming could alter the thermal conditions and distribution of frozen and frost-affected soil in the Mackenzie Delta. With warmer temperature, the permeability of sump walls could increase due to an increased thickness of the active layer and higher unfrozen water contents. Thus, sump technology which presumes the permanence of frozen soil may not be a secure means of waste containment in the long term with predicted warmer climatic conditions.

Investigating drilling-mud sumps in the Mackenzie Delta provides an opportunity to evaluate the effectiveness of frost-affected soils to contain contaminants over the long term. Many sumps in the Mackenzie Delta have existed for up to 20 years (Piteau Engineering Ltd., 1988). Investigating the long term success of northern sump disposal technology would provide useful information for government, industry, and northern residents, since contaminant leaks from disposal sites in the Arctic could result in environmental and socioeconomic problems (McLean, 1993).

1.2 Scope of Research and Objectives

1.2.1 Objectives

This thesis has two main objectives. First, it examines the long term effectiveness of frost-affected soils to contain wastes within two exploration

drilling-mud sumps in the Mackenzie Delta, Northwest Territories. Second, laboratory studies examine the role of thawed cryogenic structures in the movement of a soluble contaminant, potassium chloride, by diffusion. The second objective compliments the field studies by examining cryogenic processes which could promote solute transport away from disposal sites.

1.2.2 Field Investigations

The long term effectiveness of frost-affected soils to contain wastes was investigated by examining two sumps constructed in the mid 1970s. Kumak E-58 and Niglintgak B-19 are located on the east side of the Mackenzie Delta, in the Caribou Hills of the Northwest Territories. Each sump retained brine-based drilling-muds which contained potassium chloride (KCl) in significant concentrations up to 10 percent (J. Gayle, personal communication, 1992). Potassium chloride was added to the drilling-muds to prevent freezing during winter drilling. Since potassium chloride is not a representative constituent in the natural soils of the Mackenzie Delta (McLean, 1993), its presence in the soil can be analyzed to define movement of drilling fluids beyond sump boundaries.

1.2.3 Laboratory Experiments

Frost-affected soils exhibit physical, thermal, and hydrological properties which can change over time. Thus, understanding the processes controlling contaminant movement are complex. Past laboratory experiments have indicated

that a thawed cryogenic structure in a silty clay soil can increase hydraulic conductivity eg. Chamberlain (1989); Egginton and Dyke (1990); and Othman and Benson (1993). Laboratory experiments were conducted in this research to ascertain if solute transport by diffusive processes is accelerated due to the presence of a cryogenic structure. Examining the effect of a cryogenic structure on frost-affected soils in the laboratory will help expand the understanding of soluble contaminant movement. This information may help determine if frost-affected soil sites in the Canadian Arctic are suitable for contaminant disposal in the long term.

1.3 Thesis Overview

To facilitate an understanding of the results obtained from the field and laboratory research, several areas must be addressed. Chapter Two examines the contextual and technical background issues including: the physical geography of the field sites; the characteristics of exploration drilling-mud sumps in the Mackenzie Delta Region, as well as the major processes and factors influencing fluid and solute movement in unfrozen, frost-affected, and frozen soils. Chapter Three provides a detailed description of the methods used for both the field investigations conducted in the Mackenzie Delta and the laboratory experiments. Results of the research are presented and discussed in Chapter Four. The final chapter includes the summary of findings for both the field and laboratory investigations. Chapter Five also presents recommendations for future research.

Chapter Two

BACKGROUND ISSUES AND THEORIES

2.1 Introduction

To resolve the objectives of this thesis, two major elements must be examined. First, an appreciation of the characteristics of the Mackenzie Delta, as well as the concepts and procedures involved with exploration drilling, is essential. Second, the factors which control water and solute movement in soil must be described. It is necessary that these concepts are investigated to help determine whether drilling-mud sumps can contain fluids over a long term, and if the presence of a cryogenic structure can augment the diffusion of a solute.

2.2 Exploration Drilling in the Mackenzie Delta

2.2.1 Physical Geography of the Mackenzie Delta

The Mackenzie drainage basin covers an area of 1,842,000km². It is the second largest basin in North America (Traynor and Dallimore, 1992) and the Mackenzie Delta is located at its terminus. The Mackenzie Delta exhibits distinctive physical and biological characteristics due to its delta processes, climate, and extensive periglacial conditions (Traynor and Dallimore, 1992).

In the early Wisconsinan, erosion created a trough bound by the Caribou Hills and the Tuktoyaktuk Coastlands in the east and by the Yukon Coastal Plain and Richardson Mountains in the west (Traynor and Dallimore, 1992). This trough was later filled in with fine sands and silts up to 100m deep by delta processes in the Holocene (McLean, 1993). Since then, the outer delta area has been influenced by active delta processes and seasonal changes in water levels due to spring snow melt (Mackay, 1963). This results in the study sites having modern alluvial deposits from the Mackenzie River in addition to older Pleistocene sediments (Traynor and Dallimore, 1992).

The Mackenzie Delta is located in the arctic climatic region (Traynor and Dallimore, 1992). It is commonly depicted as having short, cool summers and long, cold winters, with a mean annual air temperature of -10°C (McLean, 1993). Precipitation is limited to only about 25cm per year and is concentrated in the period June to September (Mackay, 1963). Vegetation within the Mackenzie Delta region is governed by local topography and soil texture. At the two study sumps, the low lying areas are topped by sedge-herb species, while the well-drained locations are covered by willows (Traynor and Dallimore, 1992).

Generally, permafrost thicknesses in the Mackenzie Delta are less than 100m (Traynor and Dallimore, 1992). The thickness changes from site to site due to variation in ground materials, vegetation, and flooding. For example, summer ground temperatures near the channels in the vicinity of the field sites are shown in Figure 2.1. Figure 2.1 indicates an active layer thickness of approximately

Figure 2.1 - Temperature Profile at the Study Sites (July, 1990)

200cm. The accuracy of the temperature estimate is affected by the $\pm 0.1^{\circ}\text{C}$ accuracy of the thermistors (L.Dyke, personal communication, 1998). Research conducted by M. Nixon since 1992 in locations close to the sumps, which possess similar soil and vegetative characteristics, indicate active layer thicknesses ranging from 71cm to 119cm (personal communication, 1998). In the Mackenzie Delta, sediments contain varying quantities of ground ice in the form of lenses, veins, seams, and irregular masses (McLean, 1993) (most of the ice occurs close to the surface).

2.2.2 Exploration Drilling

Exploration drilling, which is conducted on a short-term basis to establish the location of potential oil or gas reserves, began in the Mackenzie Delta in the late 1960s (Piteau Engineering Ltd., 1988). More than 1600 oil and gas exploratory wells have been drilled in the Yukon and Northwest Territories (Piteau Engineering Ltd., 1988). In the Mackenzie Delta, approximately 20 hydrocarbon exploration wells were drilled since the late 1960s (McLean, 1993).

2.2.3 Drilling-Muds

At each site, substantial volumes of liquid and solid wastes, including drilling-muds, were produced, and disposed of, on-site due to the high cost of waste removal from the Arctic (Piteau Engineering Ltd., 1988). Rabia (1985) defines drilling-muds as a suspension of solids in oil or water. Drilling-muds

have a variable formulation and the exact composition of drilling-muds can change from site to site (Piteau Engineering Ltd., 1988).

Muds serve various functions for drilling operations (Rabia, 1985). One of the most notable is to remove rock pieces cut from the well hole. Drilling-mud is pumped down the hole to flush out the cuttings. The mud, along with the cuttings, is brought back up to the surface where rock pieces are removed, allowing the mud to be recirculated for further use. Drilling-muds also serve to cool, clean, and lubricate various parts of drilling equipment, and to provide stability to the walls of the drill hole. Furthermore, drilling-muds prevent the inflow of fluids such as oil, water, and gas, from fractures or holes on the sides of the well, and function to seal fractures and pores (Smith and James, 1979).

Drilling-muds are classified by the type of base. Three of the most common types of drilling-muds used in the Canadian Arctic are: oil based, brine based, and water based, in order of increasing usage (Piteau Engineering Ltd., 1988). Since the sums under investigation in this research utilized brine-based mud systems, only these will be discussed.

Bentonite, potassium chloride, barite, sodium hydroxide, and cellulose polymers are some of the ingredients found in brine-based muds (Piteau Engineering Ltd., 1988). Bentonite clay, the main solid component, serves to increase the density of the drilling-mud which fosters hole stability (Piteau Engineering Ltd., 1988). Solutes, such as potassium chloride, allow the drilling-mud to remain as a liquid at much colder ambient temperatures since they reduce

the freezing point of the mud. Depressing the freezing point of the mud is essential for exploration drilling because, for environmental reasons, most drilling occurs in the winter months (Piteau Engineering Ltd., 1988). The freezing point depression curve for potassium chloride solution is found in Figure 2.2 (Dean, 1973).

2.2.4 Sump Disposal and Technology

There are three main alternatives for on-site drilling waste disposal in the Canadian north: downhole disposal, land disposal, and sump disposal. Downhole disposal involves pumping clean water, along with the solid component of the drilling-muds, into the drill hole (Hardy BBT Ltd., 1988). This is the least common method of waste disposal utilized due to low ambient temperatures and logistical problems of collection, storage, and disposal of the drilling wastes (Piteau Engineering Ltd., 1988). Land disposal involves direct dumping of drilling fluids on the surface of the land and may be suitable for low-toxicity drilling-muds in areas which experience periodic flooding (French, 1978). Sumps are the most common means for on-site disposal of drilling wastes in the Mackenzie Delta. Under the Territorial Arctic Land Use Regulations, drilling-muds must be entirely contained in a below ground sump. These sumps are capped, ordinarily with the original material which was removed from the hole, after their contents have frozen (Smith and James, 1979). This capping material creates a mound of 1 to 2 metres above the local topography, which allows for

Figure 2.2 - Freezing Point Depression Curve of Potassium Chloride Solution

easy identification of the sumps, especially from the air. In continuous permafrost regions, it is customary for sump construction to involve blasting. Once permafrost materials are broken up, they are excavated by bulldozer and stockpiled for later backfilling once the sump is full with drilling waste. Since it is widely assumed that permafrost is impermeable to fluids, liners have not been used.

Construction of sumps varies according to the local permafrost conditions. Some important factors in choosing the location for a sump include: low gradient of the ground surface, distance from drainage pathways, and the avoidance of groundwater close to the surface (Hardy BBT Ltd., 1988). In addition, the soil and geological conditions should be examined (Piteau Engineering Ltd., 1988), and locations possessing large fissures or cracks should be avoided.

Sump size is determined by the anticipated depth of the well, but it is generally similar in surface area to a football field (100m x 50m x 5m deep) (Piteau Engineering Ltd., 1988). For example, for each meter drilled at an Esso wellsite in the Territories 1.3m³ of sump material is created. Petro-Canada regulations dictate that 4,000m³ to 5,000m³ of drilling-muds must be disposed of in a sump of 6,500m³ (Piteau Engineering Ltd., 1988). In addition, Petro-Canada rules state that the sump must be large enough to contain the muds no higher than 1.2m below the surrounding ground surface (Piteau Engineering Ltd., 1988), essentially below the active layer.

2.2.5 Contaminant Issues

Issues of contamination are not limited only to potential toxic effects. Environmental concerns deal with all facets of contamination. Therefore, any substance or practice which could cause objectionable substances to enter the Arctic environment is of concern (Piteau Engineering Ltd., 1988). Sump technology and disposal procedures for drilling-muds in the Mackenzie Delta are designed to allow fluids to freeze and become part of the permafrost. However, if temperatures in Figure 2.1 are representative, and given the concentration of salts within the sumps, it appears likely that sump fluids would not remain frozen over the long term.

Disposal Procedures

Disposal procedures for drilling-mud sumps dictate that backfill is added on top of the materials to compensate for settlement which may arise (French, 1978). This infilling should be performed with caution so that upwelling of any unfrozen sump fluids is avoided (Smith and James, 1985). Additionally, the weight of the infill should not be too heavy. If the weight of the overburden is too great, unfrozen fluids may be squeezed towards the surface (Smith and James, 1979). Also, excessive settlement from a depressed overburden or insufficient fill may result in a depression in the sumps. Water may collect in the depression and in turn increase the temperatures within the sump materials due to ponding. French (1978) reported that sump problems existed at Niglintgak B-19 due to the

lack of infill materials, and that the sump did have a shallow depression which collected water each spring. He also stated that this depression resulted from the melting out of ice in the sediments and volume loss during the summer.

At any site, additional sump construction should be avoided, since further construction at a site could increase the potential for terrain disturbance. Disturbances which occur before drilling fluids are frozen could result in seepage. Additionally, drilling-muds could be leaked onto the ground surface when muds are relocated from an old sump to a new sump (Smith and James, 1985). Hence, it is imperative that sumps are constructed to size at the beginning so that all drilling wastes are contained properly.

Sumps constructed over two seasons of winter drilling should be avoided. French and Smith (1980) reported that thawing of drilling fluids and sump walls occurred during the summer. Sump technology assumes the presence of frozen soil, therefore thawing of enclosing permafrost could cause seepage of sump fluids. This situation is improved when drilling and sump completion occurs within one winter.

Local Environmental Conditions

The Mackenzie Delta is an active modern delta. Therefore, drilling-muds could be mobilized if a sump is transgressed due to deltaic processes such as erosion, channel migration, and flooding from storm surges and spring run-off (Dyke, 1996)

Warm permafrost conditions in the outer Mackenzie Delta do not promote rapid freeze-back of drilling fluids (McLean, 1993). If drilling fluids are not frozen, migration could ensue. Also, chances for contamination in warm permafrost increase because solutes increase the unfrozen water content of sediments at temperatures a few degrees below 0°C (Hivon and Sego, 1990).

Solute movement downslope or within the active layer has been observed by Smith and James (1985). Elevated levels of chloride, potassium, and sodium were also found in plants surrounding three sumps in the Mackenzie Delta and three in the Peel Plateau.

Drilling-Mud Constituents

Constituents of drilling-muds could create contaminant concerns for two reasons. First barite, a major ingredient in many brine-based drilling-muds, may contribute to the presence of mercury and cadmium found in the muds (Smith and James, 1979). Metals, such as mercury and cadmium, can be harmful to all parts of the ecosystem where they bioaccumulate. Second, the composition of drilling-muds can change temporally and geographically. The chemical formulation of drilling-muds can be altered when muds interact with the rock strata below the surface and when the drilling-mud ages (Smith and James, 1979). Variations in chemical formulation of drilling-mud constituents can increase the problems of establishing criteria to assess their potential environmental impacts (Hardy BBT Ltd., 1988).

Summary

The probability of drilling-mud containment by sumps is improved if wastes are handled correctly and if the characteristics of the disposal environment are clearly understood. If present sump regulations are adequate, inconsequential amounts of contamination should have escaped from sumps into adjacent soil. Some studies, such as Smith and James (1985), have stated that sump fluids could have migrated through the active layer, but direct subsurface measurements have not verified this to date.

Regardless of past sump disposal procedures, contamination conditions could be altered with the anticipated climate change associated with global warming. An increase in temperature could increase the permeability of sump walls, and hence the chance for environmental pollution. By evaluating the performance of two sumps in the Mackenzie Delta over approximately twenty years, assessments can be made about the reliability of current sump disposal and construction practices under present climate conditions. This is important to determine if, for example, exploration for oil resources increases to full-scale in the Mackenzie Delta or if sumps are chosen for the disposal of toxic wastes.

2.3 Solute Movement in Unfrozen, Frost-Affected, and Frozen Soils

Solute movement will be considered in terms of three soil conditions: unfrozen, frost-affected, and frozen. An unfrozen soil is one which has not experienced freezing or thawing. Frost-affected soils are defined as having

experienced freezing and thawing, and thus have a developed cryogenic structure. Frozen soils, in this thesis, are those that are frozen or have been frozen for longer than 2 years (permafrost). The discussion of solute movement begins with the unfrozen condition. The most prominent soil properties affecting solute movement for each soil type are also addressed.

A definition of contaminants and solutes is essential to understand soluble contaminant movement. Contaminants are any biological, chemical, physical, or radiological substances in air, water, or soil which possess undesirable effects (Waterloo Centre For Groundwater Research, 1994). In the environment, contaminants can either be soluble or insoluble. Solutes are substances which are miscible in water.

2.3.1 Unfrozen Soils

Water Movement

There are three types of water movement in unfrozen soils: saturated flow, unsaturated flow, and vapour flow (Brady, 1990); only saturated flow will be discussed in any great detail in this paper. The three main forces moving soil water are matric potential, gravitational potential, and osmotic potential.

Matric potential results from adhesion, cohesion, and capillarity (Brady, 1990). Adhesion results when water molecules are held tightly on the soil surfaces due to the process of adsorption (Brady, 1990). Cohesion results from individual water molecules bonding to each other by hydrogen bonds.

Consequently water is held to the soil solid surface by adhesion (adsorption) and other water molecules are bonded to these water molecules by cohesion (Brady, 1990). The phenomenon of surface tension occurs at the water-air interface of a pore, and is thus more important in unsaturated soils. Since cohesion occurs between the individual water molecules, they have a greater affinity for themselves than for air. Thus, an inward force is created causing the surface of water to pull away from the air (Brady, 1990). Surface tension and adhesion influences capillarity, which is an important force controlling water movement in unsaturated porous media. The extent of movement due to capillarity is a function of the texture of the soil, as this influences the size and shape of the pores (Brady, 1990).

Water moves under gravitational potential since gravity attracts water, as with any other object or substance, towards the centre of the Earth. Gravitational potential is a function of the height of water above a given level of reference (Brady, 1990). Within saturated soil pores, water moves according to Darcy's Law:

$$Q = -k(dH/dl)A$$

where Q is the flow rate of water (cm^3s^{-1}), k is the hydraulic conductivity (cms^{-1}), which is controlled by the properties of the soil and the fluid, dH/dl is the

gradient of hydraulic head across the sample (cm/cm), and A is the cross-sectional area of the soil (cm²).

Solute Movement

The two major mechanisms of solute movement which will be discussed are diffusion and advective-dispersion. Since soluble contaminant migration is usually restricted to the fluid phase (Yong *et al.*, 1992), and by definition soluble contaminants are transported within soil water, the potentials controlling water movement will also influence solute movement.

An understanding of diffusion in unfrozen soils is essential to understand solute movement in the laboratory experiments especially where the soil was not subjected to freeze-thaw cycles. Diffusion moves ionic or molecular constituents due to their kinetic activity, in response to concentration gradients (Bedient *et al.*, 1994), and occurs in the absence of bulk flow (Freeze and Cherry, 1979). Local differences in the solute concentration are removed with time as solutes move towards the establishment of an equilibrium (Yong *et al.*, 1992). The process of diffusion occurs according to Fick's first law:

$$J = -D(dc/dz)A$$

where J is the osmotic flow (gs⁻¹), D is the diffusion coefficient for the solute (cm²s⁻¹), c is the concentration of the solute (gcm⁻³), z is the depth (cm), and A

is the cross-sectional area (cm^2) (Freeze and Cherry, 1979). The negative sign on the right hand side of the equation indicates that solute movement occurs from an area of high concentration to an area of low concentration. One can see that Fick's first law is analogous to Darcy's Law; therefore, the diffusion coefficient is affected by comparable limitations in the soil as is the hydraulic conductivity. The diffusion coefficient will be increased as the tortuosity decreases and as the water content increases (Trudgill, 1986).

It is useful to define solute movement in terms of variation with both time and depth. This can be done using Fick's second law:

$$dc/dt = D(d^2c/dz^2)$$

where dc/dt is the time rate of change of concentration and d^2c/dz^2 is the second derivative of the concentration gradient (Yong *et al.*, 1992). Fick's second law assumes: no biological or chemical reaction between the soil and the contaminant, constant volume, validity of Darcy's Law, isothermal conditions, and saturated conditions (Trudgill, 1986). In field conditions, movement of solutes by osmotic forces (molecular diffusion) is considered to be small in comparison to advective-dispersive transport (Knox *et al.*, 1993 as cited in Winnicky, 1995).

Macroscopic values of D vary for several reasons. First, in porous media, diffusion coefficients for a specific ion are reduced compared to values for D in water because the diffusion occurs over paths which are more tortuous and have

less cross-sectional area (Freeze and Cherry, 1979). Longer diffusion distances are created by highly tortuous pores. This effect has been described by several individuals. Cussler (1984), states that:

$$D_{\text{eff}} = D/r$$

where D_{eff} is the effective diffusion coefficient and r is the tortuosity. Freeze and Cherry (1979) also accounted for the effect of tortuosity by the equation:

$$D^* = wD$$

where w accounts for the reduction in the diffusion coefficient by the porous medium; values are always less than 1 and range from 0.5 to 0.01 in laboratory experiments.

The second element reducing the value of D is that diffusion in liquid-filled pores can be reduced by the viscous drag between an ion and the pore walls (Cussler, 1984). This drag effect increases as the diameter of the pore decreases.

Under certain conditions, the mechanisms of convection (advection) and dispersion are added to the effects of diffusion to fully describe solute movement. This is needed to understand solute movement in the field research conducted, but not in the laboratory research because advection was not present. Advection occurs when a solute moves at the same velocity as the water (Bedient *et al.*,

1994) and it contributes the most to solute movement within macropores when adsorptive forces between the solute and the soil surface are insignificant. Dispersion occurs when solutes distribute due to molecular diffusion and mechanical mixing (Bedient *et al.*, 1994). The equation describing advective-dispersive solute movement is:

$$J = -D^*(dc/dz) + vc_i$$

where D^* is the effective diffusion-dispersion coefficient, v is the pore water velocity in the direction z , and c_i is the concentration of the solute in question in the moving soil water (Trudgill, 1986). When examining the change in concentration of solute due to advective-dispersive movement, it is useful to express the relationship in terms of change with both time and depth:

$$dc/dt = D^*(d^2c/dz^2) - v(dc/dz)$$

The four assumptions for this relationship are: lack of significant density difference, fixed volume, no internal sources of solute, and isothermal conditions (Yong *et al.*, 1992).

Soil Factors Affecting Solute Movement

The elemental mechanisms for solute transport are well known but

difficulties arise due to solute-soil interactions and complexities of soil conditions (Trudgill, 1986). Defining solute migration will be approximated using macroscopic concepts. Soil properties which can affect solute movement are texture, structure, organic matter content, and cation exchange capacity. Since the soils investigated in this thesis have low organic matter content and low cation exchange capacity, these issues will not be discussed.

Texture describes the size distribution of particles in the soil. Generally, texture is defined by a combination of gravel, sand, silt and clay; the latter three most strongly influencing the interactions with fluids and solids (Hillel, 1982). Water migration in unfrozen soils is influenced by texture because both pore size and distribution are controlled by texture (Winnicky, 1995). For example, silts resist water movement since they have pores which are tortuous and of small diameter. Winnicky (1995) reported unfrozen silt to have hydraulic conductivities of the order of 10^{-7} to 10^{-6}ms^{-1} . Diffusivity values for clayey deposits range from 10^{-10} to $10^{-11}\text{m}^2\text{s}^{-1}$ (Freeze and Cherry, 1979). In contrast silt mixtures and fine sands have hydraulic conductivities of 10^{-6} to 10^{-4}ms^{-1} (Bowles, 1979) and diffusivity values are somewhat larger than $10^{-10}\text{m}^2\text{s}^{-1}$ (Freeze and Cherry, 1979).

Soil structure refers to the spatial arrangement of the primary soil particles into compound particles, aggregates, or peds (Hillel, 1982). Animal activity, root penetration, and cracks created by wetting and drying can often create macropores which permit rapid movement of soil water and solutes (Brady, 1990). Scotter (1979), as cited in Trudgill (1986), expressed that preferential solute movement

due to advection may occur in pores as small as 0.02cm in diameter. In addition, Ritchie *et al.* (1972), as cited in Trudgill (1986) believed that a continuous network of cracks strongly influenced the pattern of solute movement under saturated conditions. Furthermore, Lyman *et al.* (1992), as cited in Trudgill (1986), confirm that transmission can occur even if the macropores comprise only a small fraction of the total soil volume.

2.3.2 Frost-Affected Soils

An understanding of solute movement in frost-affected soils, such as occurs in an active layer, is useful to interpret the results of the field research. Also, the laboratory experiments in this thesis were conducted in soils which had experienced various freeze-thaw cycles.

Solutes will move under the same mechanisms as in unfrozen soils except that the soil structure can be changed due to the process of freezing and thawing. As soils freeze and thaw, a cryogenic structure is created which can change the permeability of the soil, in a way that depends on the texture and number of freeze-thaw cycles.

Chamberlain (1989) believes an increase of permeability in fine-grained soils occurs due to the cracks left by melted ice lenses. These cryogenic discontinuities constitute paths with lower flow resistance than the interstitial paths followed before freezing. Chamberlain and Gow (1978) found that freezing and thawing augmented the permeability of saturated clay by three orders of

magnitude. Similarly, Eigenbrod (1996) found that cyclical freezing and thawing of fine-grained soils increased the permeability often by two orders of magnitude.

Chamberlain *et al.* (1997) found that in a sand-bentonite mixture, the hydraulic conductivity was neither augmented or reduced by freeze-thaw cycles. However, Wong and Haug (1991) reported a decrease in hydraulic conductivity of sand-bentonite mixtures with freeze-thaw; they suggested consolidation was responsible for the decrease. Sand is relatively incompressible and can resist freeze-thaw consolidation; the permeability of a sand-bentonite mixture could decrease since thaw consolidation could push the finer bentonite grains into gaps between sand grains. In coarser textures, fewer cracks are created during freezing and thawing (Chamberlain *et al.*, 1997) and any fissures that are created do not stay intact when the material thaws.

Observed increases in permeability are also influenced by the number of freeze-thaw cycles. Othman and Benson (1993) and Wong and Haug (1991) found freezing and thawing increased the permeability of fine-grained soils up to three freeze-thaw cycles and three to five freeze-thaw cycles respectively. They believe that creation of lenses in new locations beyond the reported number of freeze-thaw cycles became negligible.

Direct field measurements of solute distribution in the active layer were made by Lewkowicz and French (1982). They determined that solute concentrations increased with depth in the active layer due to increased solute residence time resulting from longer flow paths in time and space. For example,

solutes transported to lower layers due to a combination of freeze-thaw cycling and infiltration by rain or snow melt, will remain at these lower depths for longer time periods since water flow is reduced at these depths.

2.3.3 Frozen Soils

Examining solute movement in frozen soils is necessary to understand solute movement in permafrost or in the active layer when soil temperatures are below 0°C. The movement of water in frozen soil is comparable to the movement of water in unsaturated unfrozen soil, except that the movement is isolated to the unfrozen water films (Anderson and Morgenstern, 1973) and ice replaces air. Figure 2.3 summarizes the effect of temperature on the hydraulic conductivity of saturated, frozen soil for various soil textures (Williams and Smith, 1989). It is apparent that the hydraulic conductivity decreases sharply a few tenths of a degree below 0°C because of the dependence of hydraulic conductivity on the thickness of unfrozen water films. Since solutes are transported in water, the possibility exists for solutes to move in frozen soil under the same gradients moving liquid water in unfrozen unsaturated soil. The amount of unfrozen water in a frozen soil is controlled by soil texture, solute content, and temperature, which can be explained using soil energy concepts.

According to Brady (1990), the sum of all forms of energy in soil water available to do work is termed free energy. The freezing point of a soil solution

Figure 2.3 - Hydraulic Conductivity vs. Temperature for Saturated Frozen Soil of Various Textures

will be depressed when the free energy of the solution decreases. This phenomenon is controlled by solute content and matric forces such as adsorption and capillarity (Williams and Smith, 1989), and it can increase the thickness of water films in the soil. In natural soils, this effect is usually only responsible for approximately 0.1°C depression in the freezing point below 0°C but it will be greater in soils contaminated by solutes. Once ice begins to form in soil pores, the freezing point drops further due to matric forces becoming more important. Adsorption, created by forces from the surfaces of soil particles, reduces the free energy of the soil solution which is confined to thin layers on soil particles. Therefore, lower temperatures are required to convert these adsorbed water films to ice (Williams and Smith, 1989).

Movement of solutes through unfrozen water films in the frozen state occurs due to the three dominant gradients of temperature, concentration, and hydrostatic pressure (Qui *et al.*, 1988). Solutes move within the water from an area of warm temperature to an area of cooler temperature (Qui *et al.*, 1988). This results in the migration of solutes towards the freezing front. Solutes also move due to concentration differences and it is believed to be the principal process regulating fluid movement in frozen soils (Winnicky, 1995). Therefore, solutes diffuse from an area of high concentration to an area of low concentration (Qui *et al.*, 1988). This process causes solutes to move away from the freezing front since freezing causes the soil there to have a high concentration of solutes.

Solute movement in frozen soils is also influenced when water freezing causes solutes (impurities) to be rejected from ice (Panday and Corapcioglu, 1990). Rejection of solutes occurs because solutes are not soluble in the ice phase of water. Solute rejection is controlled by the cooling rate of frozen soil. According to Konrad and McCammon (1990) 90 percent of solutes are rejected from pore ice when cooling rates similar to field conditions occur ($0.1^{\circ}\text{C}/\text{day}$) in saturated clayey silt. They also concluded that solute rejection did not occur when cooling was greater than $3^{\circ}\text{C}/\text{day}$. Therefore, high freezing rates result in reduced solute-expulsion and entrapment of solutes in the frozen zone (Kay and Groenvelt, 1983).

Chapter Three

METHODOLOGY

3.1 Introduction

The methodology of this project is composed of two elements. The first involves the field procedures associated with the first objective of this thesis: a detailed description of the selection of the field sites, sample analysis, determination of soil properties, and pore water removal and analysis. The second element involves laboratory procedures: explanation of apparatus, method of data collection, preparation of samples, as well as experimental protocol.

3.2 Field Investigations

Field investigations to examine two drilling-mud sumps were carried out during April, 1997 in the Mackenzie Delta. The locations of Kumak E-58 and Niglintgak B-19 sumps are shown in Figure 3.1. Both sumps were constructed by Shell Canada Limited in the mid 1970s.

Figure 3.1 - Location of Field Sites

3.2.1 Site Selection

Over 1500 sumps exist in the Northwest Territories (Hardy BBT, 1988) and approximately 20 of these are in the Mackenzie Delta (McLean, 1993). Kumak E-58 and Niglintgak B-19 were chosen for several reasons. First, the types and amounts of substances present in the sumps were documented in detail by Shell Canada Limited (J. Gayle, personal communication, 1992). Since potassium chloride occurred in both sumps in concentrations up to 10 percent it was chosen as the tracer for assessment of contaminant leakage.

Second, the dates of the sumps were known and the period of disposal of drilling fluids was short compared to the length of time both sumps have now existed (Dyke, 1996). Both sumps can be considered as long term sources of contaminants since they have existed for approximately twenty years.

Furthermore, previous work by Hardy BBT (1988) and Nenniger (1987) suggested that inductive conductivity techniques, such as EM31, can be used to observe solute-rich fluids within and around drilling-mud sumps. Higher ground electrical conductivities are believed to be associated with the presence of saline sediments, taliks, or zones of warm permafrost (Dyke, 1996). Readings greater than 2 to 3mmho/m indicate the influence of salt or thawed or partially thawed sediments (Nenniger, 1987). Evidence of solutes concentrating at sump boundaries and just outside the boundaries was shown by an EM31 survey carried out by M. Douma and C. Hyde (personal communication, 1997) in April, 1997. Since sediments would be frozen during April, any values above 3mmho/m would

indicate the presence of salty drilling fluids. Results from their survey are shown in Figures 3.2 and 3.3 (units are in mmho/m). The thick black lines in Figures 3.2 and 3.3 are the sump boundaries and should not be confused with the thinner lines representing the isolines for conductivity values. Borehole locations for each sump are also shown in Figures 3.2 and 3.3. Both figures illustrate higher values with the vertical dipole (penetration depth of approximately 3m) when compared to the horizontal dipole (penetration to approximately 6m). This would indicate a higher concentration of sump fluids towards the surface.

Direct sub-surface investigations at both Kumak E-58 and Niglintgak B-19 were intended to provide information about the migration of solutes or the presence of sediment conditions conducive to fluid movement. The two sumps were in proximity to each other and were within a short flying distance from Inuvik, the base for the field research. These conditions reduced travel time and therefore made the planned investigations economical and logistically feasible.

3.2.2 Field Methodology

Continuous frozen core was collected from three boreholes at each sump. Drilling occurred along a transect which started within the sump boundaries and extended out into undisturbed delta or upland Pleistocene sediments. Sump boundaries were approximated using information from a previous field survey (McLean, 1993). Borehole depths ranged from 94cm to 233cm; approximately

Figure 3.2 - EM31 Survey of Kumak E-58 - Including Borehole Locations
Units in mmho/m

Figure 3.3 - EM31 Survey Niglintgak B-19 - Including Borehole Locations
Units in mmho/m

30cm of core was removed at a time. Characteristics of all core were noted before a sample of approximately 8cm in length was broken off using a chisel and a hammer. The samples were then placed into marked 500ml plastic screw-top containers and tightly sealed to prevent moisture loss. Samples were kept in freezer storage at the Inuvik Research Laboratory.

3.2.3 Analysis of Samples

General Soil Properties

All samples were assessed for gravimetric water content using standard methods. Soil samples of approximately 60g to 70g were oven dried at 105°C for 24 hours. Samples were removed and then the error in weighing was ± 0.01 g.

A portion of the field samples was retained in marked plastic bags after water content analysis was completed. This was used to determine soil texture, organic matter content, unfrozen water content, and effective cation exchange capacity.

Standard procedures outlined in Torrance and Patterson (1990) were used for grain-size determinations of samples. All weights had an error of ± 0.01 g. Soil texture was determined using a standard soil texture triangle from Bridges (1991).

Organic matter content of samples was determined using standard procedures described by Rowell (1994). Procedures were modified under the guidance of Dr. Ken Torrance. Samples were heated in a Muffle furnace at 325°C

for three hours instead of 400°C for three hours. This reduction in temperature during heating of the samples prevented the alteration of any clay fraction present in the soil; which would cause an overestimation in the amount of organic matter present in the soil sample (J.K. Torrance, personal communication, 1997). Error for all weights was $\pm 0.01\text{g}$.

Time domain reflectometry (TDR) was utilized to determine the unfrozen water content. Procedures implemented were specified by Patterson and Smith (1980) and possess a standard error of 1.5 percent (Smith and Tice, 1988). Samples were frozen to -10°C and TDR traces were recorded at various temperatures as the samples were warmed to 0°C .

Effective cation exchange capacity (CEC) was determined following the procedures outlined by Sheldrick (1994). After preparation, the relative concentration (ppm) of calcium, magnesium, and potassium were determined by atomic absorption spectroscopy at the Biology Department at Carleton University. Concentration values were recorded to $\pm 0.01\text{ppm}$.

Pore Water Removal and Analysis

Pore water was removed from field samples using a manual compaction method. Specimens were first stirred to achieve a uniform consistency. Then approximately 35cm^3 of soil was compacted using a standard soil compacting device. Pore water was removed by extending the plunger onto the sample, which was confined by a metal tube. The water removed was collected in a clean watch

glass and was poured into a clean marked 20ml plastic bottle. Equipment was then cleaned with deionized water and left to air dry between repeats. This procedure was duplicated until a pore water sample of at least 3ml to 5ml was collected. Samples were centrifuged at 1800rpm for 30 minutes. Clear pore water was decanted and placed into new, clean labelled 20ml bottles.

Pore water extracted from the majority of field samples was analyzed by inductively coupled plasma (ICP) to determine levels of major cations and anions, and since potassium and chloride are associated with drilling fluids, they were the ions analyzed in this research. Several field specimens were kept frozen at the time the samples were prepared for ICP analysis, therefore cation and anion data were not collected. Standard procedures were completed by the Ion Chromatography Laboratory at the Geological Survey of Canada. Levels of potassium, calcium, sodium, sulphate, and chloride were determined to ± 0.1 ppm.

Electrical conductivity values were determined, using a conductivity/salinity meter, for all field samples, including the samples which were not sent for ICP analysis. The meter was calibrated using standard potassium chloride solutions created using reagent grade potassium chloride. Values of electrical conductivity were determined in millimho (mmho) per centimetre to a precision of ± 0.01 mmho/cm.

Considering that electrical conductivity measurements were determined for all soil samples, using electrical conductivity to understand the behaviour of potassium and chloride would be useful. First, a statistical package was used to

determine if the data were normally distributed and transformations were performed if necessary. A multiple correlation analysis was performed to determine if electrical conductivity values were associated significantly with corresponding concentrations of chloride and potassium. In addition, a bivariate correlation analysis was performed to determine if the correlation between electrical conductivity and the individual ions was significant.

3.3 Laboratory Studies

Three large-scale box experiments were conducted to examine the influence of a thawed cryogenic fabric on the diffusion of a soluble contaminant (potassium chloride). In two experiments the prepared soil was subjected to freeze-thaw cycling prior to the diffusion experiment. Samples were contaminated from one end of the sample by a reservoir filled with a potassium chloride solution when they began thawing. A third experiment was conducted where the sample was not subjected to freeze-thaw cycles and thus did not possess a cryogenic structure.

3.3.1 Description of Soil Container

Two large wood boxes (Figure 3.4), having internal dimensions of approximately 70cm long, 30cm wide and 37.5cm high, were available from the

Figure 3.4 - Diagram of Soil Container

Geological Survey of Canada. The large size of the soil container is intended to approximate the field scale of interest to this thesis, as opposed to a more conventional permeameter apparatus.

The boxes were insulated on all sides with 5cm of styrofoam to allow for one dimensional top-down freezing during experiments. A thick plastic sheet was placed between the styrofoam and the outside wood to prevent leakage. Another plastic sheet lined the inside of the box to prevent leakage when saturated soil was added to the box.

In many previous experiments, e.g., Baker *et al.* (1990); Baker and Osterkamp (1989); Panday and Coropcioglu (1991), soil was saturated with a solute before freezing and only vertical solute movement was examined. In contrast, the apparatus in this thesis was arranged to investigate horizontal migration of salt into an uncontaminated thawed or unfrozen soil. A plexiglass reservoir, of approximately 27cm by 6.5cm, was located at one end of the box to contain a solution of potassium chloride. The side of the reservoir exposed to the soil was perforated permitting continuous solution contact with the soil during the experiments. A silk cover prevented soil from clogging the screen or entering the reservoir. To prevent water from entering the reservoir during infilling of the boxes, it was filled with a slab of 5cm thick insulation wrapped in plastic. The insulation also functioned to insulate the side of the sample exposed to the reservoir during freezing.

3.3.2 Preparation of Samples

Due to the logistical complications of removing soil from the Mackenzie Delta during the month of April and the potential cost of shipping the large amount of soil required for the experiments, a local soil was used for the experiments. This soil was chosen because it was available in large quantities and it had a consistent texture containing silt. Thus, the experimental soil was deemed likely to develop a cryogenic structure. General soil properties were determined for the experimental soil following the procedures outlined in section 3.2.3.

For each experiment, samples were prepared to achieve saturated gravimetric water contents equalling approximately 40 percent. During mixing all previous soil structure was destroyed. Therefore, water contents and soil structure characteristics in all experiments were assumed to be similar.

Comparable wet bulk densities for experiments were achieved by following similar packing procedures for each experiment. For each experiment, the box was filled with saturated soil in layers of 5cm. Sensors (thermistors or conductivity probes) for the experiment which experienced one freeze-thaw cycle, were placed into the soil as the boxes were filled. For the other two experiments, the sensors were mounted on a plexiglass rod at defined distances. String, attached to the ends of the rods, was secured to the sides of the soil container. The rod was then suspended at the required height within the soil. This improvement was completed to increase the accuracy of probe locations. The

surface of the soil was packed equally by gently tapping each 10cm² of the surface 5 times with a flat surface. This continued until the depth of soil in the box was approximately 22cm. The soil was then allowed to settle under its own weight for 24 hours achieving a final soil depth of approximately 20cm.

3.3.3 Experimental Protocol

Othman and Benson (1993) and Wong and Haug (1991) determined that the permeability of a fine-grained soil increased with freeze-thaw up to three to five cycles. Beyond three to five cycles, the cryogenic structure did not change significantly. On this basis, one and three freeze-thaw cycles were chosen for the experiments in this thesis.

For all experiments, tap water was used to saturate the soil and to create the 1 percent potassium chloride solutions. The solute concentration was limited to this value since the conductivity device could only measure up to this level. A thick plastic sheet covered the top of the soil during experiments to prevent moisture loss. All experiments occurred at a room temperature of approximately 20°C.

In the first experiment, the soil was subjected to one freeze-thaw cycle. At the beginning of the thaw cycle, the reservoir was filled with the solution. Five conductivity probes and thermistors were buried at two depths (10cm and 19cm) and several distances (2.5cm, 5cm, and 10cm) from the reservoir. After the box was filled it was placed in a cold room at a temperature of -5°C. Once

the thermistors indicated the bottom of the box was frozen, it was removed from the cold room. The insulation was removed from the reservoir and a pre-cooled 1 percent potassium chloride solution filled the reservoir to the height equal to the soil depth. The solution was chilled to slow down the effect of the solution thawing the sides of the soil beyond surface thawing effects. Insulation was placed on the top of the reservoir to keep the contaminant source cool.

The same procedures used for the single freeze-thaw cycle were used for the experiment which experienced three freeze-thaw cycles, except for two differences. First, a reduced soil volume was used to reduce preparation time. Soil filled the box to a distance of 35cm from the reservoir. Also, the 1 percent KCl solution was introduced at the beginning of the third thawing cycle.

In the third experiment, the soil volume was also reduced to fill the box to 35cm from the reservoir. Otherwise, the sample was wetted and compacted as in the other two experiments. Once the sample was allowed to settle, monitoring of the conductivity probes began when the solution of potassium chloride at room temperature was added to the reservoir.

3.3.4 Method of Data Collection and Analysis

Freezing and Thawing Rates

Freezing and thawing rates for experiments were determined in mm/hr using Fenwal thermistors calibrated by V. Allen of the Geological Survey of Canada. Resistance was recorded to the nearest ohm and then converted to

temperature using the corresponding calibration equations. Temperature measurements have an error of $\pm 0.001^{\circ}\text{C}$.

Conductivity Probes

Conductivity in the soil was monitored during the experiments using conductivity probes constructed by R. Branker. Measurement from conductivity probes were made at least every hour by a six channel conductometer. The sensitivities of each probe used in each experiment are shown in the Table 3.2. Sensitivity of each probe was defined as:

$$\frac{\text{Final Electrical Conductivity} - \text{Initial Electrical Conductivity}}{\text{Final Voltage} - \text{Initial Voltage}}$$

and was used to convert output voltages to electrical conductivity values. Before final electrical conductivity values were calculated, initial background voltages were subtracted; consequently, electrical conductivity values represented the change from initial conditions. Calculated sensitivities assumed linear behaviour and that pore water extraction sampling locations described the behaviour observed for the conductivity probes. Probes at the locations of 10cm distance from the reservoir and 10cm depth in all experiments were excluded; these probes did not behave consistently.

Table 3.1 - Probe Sensitivities

EXPERIMENT	DISTANCE FROM RESERVOIR (cm)	DEPTH IN BOX (cm)	SENSITIVITY (mmho/cm)/V
1	2.5	10	4.43
1	2.5	19	2.77
1	5	10	7.34
1	5	19	2.81
1	10	10	13.45
2	2.5	10	4.96
2	2.5	19	3.52
2	5	10	8.22
2	5	19	3.31
2	10	10	-24.73
3	2.5	10	4.66
3	2.5	19	4.20
3	5	10	5.67
3	5	19	3.98
3	10	10	-8.33

Pore Water Extraction

To assess the movement of potassium chloride at the end of the experiments, soil samples, representing the top 10cm and bottom 10cm of soil in the box were excavated, at several distances from the reservoir. Pore water was removed from the soil samples using manual compaction methods outlined in section 3.2.3 and values of electrical conductivity were measured. Initial electrical conductivity values present at the beginning of the experiment were subtracted from the observed electrical conductivity values, and these new values were converted to percentages of potassium chloride using Figure 3.5 (Dean, 1973). Also, initial and final values of electrical conductivity were utilized to determine the sensitivity of each conductivity probe.

To help with the analysis, percentages of potassium chloride were converted to grams of potassium chloride. Before this could be done, several calculations were completed. First, since the horizontal distances between pore water extraction sampling locations were not equal, the calculated percentages of potassium chloride represented different volumes of soil. To determine the volumes represented for each specimen, the total volume of the boxes was divided first vertically into two 10cm depths (0-10cm and 10-20cm), and second horizontally, by dividing the horizontal distances between specimens equally. This method weighted the larger volumes more heavily than the smaller volumes.

Figure 3.5 - Electrical Conductivity vs. Concentration of Potassium Chloride

The calculated volumes and corresponding horizontal dividing distances between the sampling locations from the reservoir are illustrated below.

0cm	3.75cm	7.5cm	12.5cm	17.5cm
1125cm ³	1125cm ³	1500cm ³	1500cm ³	
1125cm ³	1125cm ³	1500cm ³	1500cm ³	

Second, the values of gravimetric water content and wet bulk density were used to calculate the weight of water in a given soil volume; which was necessary to determine the weight of potassium chloride associated with the percentages of potassium chloride for a given volume. Soil volumes associated with similar sampling locations between experiments would be identical but the total weight of water in each soil volume could vary slightly between experiments if differences in gravimetric water content and/or wet bulk density existed between experiments. Calculations assumed that potassium chloride was uniformly distributed throughout the corresponding volume of soil.

Chapter Four

RESULTS

4.1 Introduction

This chapter will present and discuss the results for both the field and laboratory research. Results for field studies are presented first and include: a description of borehole samples, an account of soil properties, as well as the outcome from pore water samples. Laboratory results include: a report of soil properties, freezing and thawing rates, pore water extraction measurements, and conductivity probe monitoring.

4.2 Field Investigations

4.2.1 Borehole Descriptions

At each sump, three boreholes were drilled to give a total of 44 samples. At sump boundaries, samples were from both within the active layer and below the active layer. Outside of sump boundaries, samples were only from the active layer. A description of all samples was recorded and included comments on the type of cryogenic structure, texture, and organic matter content. These three elements will be summarized for sediments within the sump and surrounding the

sump.

Sediments outside of the sumps contained both laminar and reticulate cryostructures with veins and lenses several millimetres in thickness. Sediments were composed of fine silt, fine sand, and clay. In addition, subhorizontal laminations with cross bedding were often present, indicating that sediments were deposited by water. Organic detritus, small roots, and buried grasses were present in the sediments most often as localized layers at depth within the profiles. Localized layers of organic roots and grasses within the profile are an indication of past soil surfaces which have since been buried by delta sediments or cryoturbation.

In general, the cryostructure of sediments within the sumps was similar to the sediments outside the sump except a massive structure containing remoulded clasts with interstitial ice was also represented. The massive structure including clasts was created because the surficial sump materials were remoulded by procedures such as blasting, stockpiling, and infilling. Texture and organic matter content for the sump materials were comparable to sediments outside the sump, however fewer localized organic layers were present.

4.2.2 Soil Properties

The results for texture, organic matter content, effective cation exchange capacity, and gravimetric water content analysis are presented in Table 4.1. Figure 4.1 depicts the unfrozen water content curve. All soil properties were

Table 4.1 - Average Soil Properties of the Field Soil

SOIL PROPERTY	VALUE
Texture	Sand = 4.1% Silt = 93.8% Clay = 2.1%
Organic Matter Content	3.63%
Effective Cation Exchange Capacity	Ca = 6.06meq/100g Mg = 0.65meq/100g K = 1.96meq/100g Total = 8.67meq/100g
Gravimetric Water Content	38.52%

Figure 4.1 - Average Unfrozen Water Content Curve of the Field Soil

determined for sediments outside the sump.

From the grain size analysis, the sediments are classified as silt. This texture corresponds to the fine textures deposited by delta processes. In general, the organic matter contents are less than 4 percent since the local vegetation has a short growing season and the decomposition of organic matter content is slow. Cation exchange capacity values below 9meq/100g are due to the low contents of organic matter and clay. Also, low unfrozen water contents are present due to the lack of clay which results in soils having low hydraulic conductivity values a few tenths of a degree below 0°C. Gravimetric water contents for the majority of sediments both within and outside the sump boundaries were high due to the prominence of ice.

4.2.3 Pore Water Results and Analysis

Profiles illustrating the concentration of potassium and chloride with depth for each borehole are shown in Figure 4.2 and Figure 4.3. A statistical analysis revealed that the log of potassium, log of chloride, and the square root of electrical conductivity were normally distributed. Therefore, a multiple correlation was performed and it revealed that the electrical conductivity values for the sumps were correlated significantly, at the 95% confidence level, with potassium and chloride ($R=0.92$). Consequently, the behaviour of electrical conductivity was related to the behaviour of potassium and chloride. However, since chloride can occur naturally in the soil up to several percent due to past

Figure 4.2 - Concentration of K and Cl vs. Depth at Kumak E-58

Figure 4.3 - Concentration of K and Cl vs. Depth at Niglintgak B-19

storm surges (a correlation between chloride and sodium concentrations of 0.94 confirms this hypothesis), and potassium occurs naturally in the soil at only a few ppm (Dyke, 1996), more confidence would exist in using the presence of potassium to locate leaked drilling fluids. A bivariate correlation analysis was performed and indicated that electrical conductivity was significantly correlated, at the 95% confidence level, with potassium ($R=0.82$). Notwithstanding that this correlation is a little lower than with chloride, the variation of electrical conductivity will be used to understand the variation of potassium.

Figures 4.4 and 4.5 present the values of electrical conductivity associated with field samples. Generally, the graphs show that electrical conductivity values are higher at sump boundaries than outside sump boundaries. However, the lower values at 5m and 10m from the sump boundaries still exceed expected values for local uncontaminated conditions. Reasons for these general patterns, as well as other details about the graphs, will be discussed in the subsequent two sections.

Sump Boundaries

The top graphs in Figures 4.4 and 4.5 present the values of electrical conductivity associated with the boreholes just inside sump boundaries at Kumak E-58 and Niglintgak B-19 (See Figure 3.2 and 3.3 for exact location). Approximately the first 200cm of Kumak E-58 and the first 160cm of Niglintgak B-19 of the boreholes within the sumps correspond to sump fill material which

Figure 4.4 - Electrical Conductivity vs. Depth at Kumak E-58

Figure 4.5 - Electrical Conductivity vs. Depth at Niglintgak B-19

showed evidence, by the electrical conductivity values, of potassium levels greater than background values. Thus, drilling contaminants were present within the fill materials. Values of electrical conductivity peaked around 135cm at Kumak E-58 and 150cm at Niglintgak B-19; below that depth, values of electrical conductivity dropped to background levels at approximately 230cm and 175cm respectively. At those depths, low values of electrical conductivity were associated with an ice layer. In sumps containing saline drilling-muds, a layer of ice was often introduced between the most saline drilling-muds and the fill materials. The function of the ice layer was to prevent fill materials from collapsing into saline drilling-muds (L. Dyke, personal communication, 1998), which may not have been totally frozen at the time of infill. Unfortunately, samples were not taken from deeper than 230cm (Kumak E-58) and 205cm (Niglintgak B-19) due to technical problems. At Kumak E-58 the barrel of the corer got stuck which forced abandonment of the hole. Similarly, the borehole within Niglintgak B-19 was abandoned when plywood was encountered.

Outside of Sump Boundaries

In general, values of electrical conductivity within boreholes outside the sump increased to beyond background levels with depth (Figures 4.4 and 4.5). Values of electrical conductivity did not drop substantially with distance from the

sump boundary indicating sump contaminants likely extended beyond the distances observed.

All borehole samples taken outside the sump were within the active layer according to the observed active layer thickness stated by Traynor and Dallimore (1992) and Nixon (personal communication, 1998). Concentration of potassium increased with depth within the active layer for all boreholes, and this is believed to be for several reasons.

Fundamentals of disposal procedures in the Mackenzie Delta dictate that all muds be disposed of in one winter to avoid terrain disturbances (French and Smith, 1980). Thus, companies are under time constraints to construct the sump, drill the hole, and dispose of wastes, all within a single winter. Once the drilling-muds, containing up to 10 percent potassium chloride by mass, are disposed of in the sump, procedures state that drilling-muds should be frozen before the capping material is placed on top of the muds. Since the disposal of wastes and capping of material must occur within one winter, and the freezing point depression of 10 percent potassium chloride solution is 4.8°C (Figure 2.2), there is the possibility that a portion of the drilling-muds would remain unfrozen. It is postulated that when the sump was capped unfrozen drilling fluids were upwelled from depths below the active layer, towards the surface between the sump backfill materials and the sump walls.

Niglintgak B-19 may have experienced upwelling of unfrozen drilling fluids after sump closure since the sump had a settlement depression (cf. French, 1978). Therefore, even though the drilling-muds are routinely contained below the capping materials and the active layer, the fluids would then be exposed to the capping material and the walls of the sump within the active layer. Displacement of drilling fluids would result in higher concentrations of potassium chloride along the sides and just outside of the sumps. This pattern was shown by the electrical conductivity data in this research and by the EM31 survey for Kumak E-58 and Niglintgak B-19 completed by M. Douma and C. Hyde (personal communication, 1997). EM31 results showed that drilling fluids may have moved at least 10m from Kumak E-58 and Niglintgak B-19. This is consistent with the suggestion that drilling fluids may have escaped along sump walls. Other EM31 surveys, completed on sumps by Nenniger (1987) and M. Douma and C. Hyde (personal communication, 1997), demonstrated similar patterns of surface electrical conductivities.

Drilling solutes exposed to the fill materials and the active layer could be rendered mobile because both thaw every year. Once thawed, unfrozen water provides an avenue for solute movement by advection and/or diffusion. This mobility could be increased beyond that expected for unfrozen silt since the capping material and sediments within the active layer at these sumps have been exposed to freeze-thaw cycles. Numerous studies have indicated that the

hydraulic conductivity of fine-grained soils is increased when the cryogenic structure thaws (cf. Chamberlain and Gow, 1978; Eggington and Dyke, 1990; Eigenbrod, 1996). The maximum possible movement of drilling fluids over 20 years, using the hydraulic conductivity of lensed silt (10^{-6}ms^{-1}) and sandy loam (10^{-5}ms^{-1}) used in the laboratory experiments, would be approximately 10m to 100m respectively. This calculation seems reasonable since drilling contaminants were measured up to 10m from the sump boundaries. This calculation assumes: solute movement only by advection, no interaction between the solutes and the surrounding sediments, and thawing occurring from mid-May to mid-September (122 days) each year. Gravitational gradients are believed to have contributed to advective flow over the last 20 years since the elevations of both sumps are a few meters above the surrounding sediments.

Hydraulic conductivity values for frozen lensed silt at -0.5°C would be approximately four orders of magnitude less than the unfrozen soil (Figure 2.3). This magnitude would be further reduced during most of the winter when surface temperatures range from -8°C to -6°C , due to the reduction in unfrozen water content. At the field sites, unfrozen water contents in sediments, not contaminated by drilling fluids, are only significant within a few tenths below 0°C (Figure 4.1). The effect of drilling solutes depressing the freezing point of water within the soil at winter surface temperatures would only be significant when concentrations exceeded 12 percent potassium chloride (Figure 2.2). Since the

highest concentration of potassium or chloride observed in boreholes did not exceed 0.4% and 0.7% respectively, concentrations of greater than 12 percent potassium chloride would only be present in very small pores. Accordingly, solute movement over the past 20 winters would be minimal.

The pattern of increasing concentration of drilling solutes at depth within the active layer is believed to occur for several reasons. First, freezing is responsible for rejection of solutes in the soil (Konrad and McCammon, 1990). Solute rejection would be primarily downwards within the active layer due to an advancing frost front in the fall. Also, water from snow melt and rain would infiltrate into the active layer and solutes present in the soil would be transported towards the base of the active layer. Longer flow paths and low water flow at depth in the active layer would increase the residence time of solutes (Lewkowicz and French, 1982). Furthermore, solutes travelling downwards within the active layer will be confined at the base by permafrost which has a low permeability and does not thaw. This confinement of solutes by permafrost could change if the distribution or characteristics of permafrost are changed for any reason, such as climate change.

Unfortunately, samples were not obtained from within permafrost from outside the sump boundaries. Technical problems and time constraints prevented the acquisition of soil samples below the active layer. Therefore, conclusions based on direct soil measurements cannot be made to assess drilling solute

movement within permafrost from sumps over the last 20 years. However, the previous calculations for frozen soil indicate movement would likely be very small.

4.3 Laboratory Studies

4.3.1 Soil Properties

Texture, organic matter content, effective cation exchange capacity characteristics of the experimental soil are shown in Table 4.2. The soil is classified as a sandy loam, with low organic matter content, and low effective cation exchange capacity. Therefore, during the experiments adsorption of potassium chloride by the soil was assumed to be insignificant. Table 4.2 also summarizes the wet bulk densities and gravimetric water contents for all three experiments. Wet bulk density measurements represent random measurements taken within the soil containers at the end of the experiment. Gravimetric water contents were taken from each batch of soil created to fill the soil containers at the beginning of the experiment. Figure 4.6 is the unfrozen water content curve for the experimental soil and is comparable to unfrozen water content characteristics of the field soil. This similarity is reasonable since both soils have low clay content.

Table 4.2 - Soil Properties of the Experimental Soil

SOIL PROPERTY	VALUE
Texture	Sand = 53.6% Silt = 45.5% Clay = 0.9%
Organic Matter Content	3.78%
Effective Cation Exchange Capacity	Ca = 9.09meq/100g Mg = 1.49meq/100g K = 1.16meq/100g Total = 11.74meq/100g
Wet Bulk Density	Structureless (SE) - 1.74g/cm ³ 1FTC - 1.76g/cm ³ 3FTC - 1.76g/cm ³
Gravimetric Water Content	Structureless (SE) - 40.69% 1FTC - 40.74% 3FTC - 40.87%

Figure 4.6 - Unfrozen Water Content Curve of the Experimental Soil

4.3.2 Freezing and Thawing Rates

Freezing and thawing rates were calculated for the first experiment which experienced one freeze-thaw cycle (1FTC). The freezing and thawing rates were 1.04mm/hr and 3.10mm/hr respectively. These rates were assumed to be similar to the experiment which experienced three freeze-thaw cycles (3FTC) since it possessed similar soil properties, was prepared using identical procedures, and was exposed to comparable temperatures during freezing and thawing.

4.3.3 Conductivity Results

Figure 4.7 shows the electrical conductivity data for the entire 25 days of the experiments. On the graphs, the occasional large drops in electrical conductivity are the result of equipment malfunction. In each experiment, four probes monitored the progress of diffusion.

Expected diffusive patterns over time for these experiments could be different from the standard case for two main reasons. The standard case is defined as an experiment where the concentration in the reservoir remains constant throughout the entire experiment. Therefore, after a given time period the concentration in the soil will approach the constant concentration in the reservoir, which is equal to the initial value (See Figure 4.8). In these experiments, since the concentration of potassium chloride in the reservoir was allowed to drop during the experiments, the final electrical conductivity for the probes would approach the final equilibrium value, rather than the initial value.

Figure 4.7 - Electrical Conductivity vs. Time for the Experiments

STRUCTURELESS

ONE FREEZE-THAW CYCLE

THREE FREEZE-THAW CYCLES

Figure 4.8 - Pattern of Diffusion: Concentration vs. Time

Constant Concentration Source (Trudgill, 1986)

Also, for probes at distances close to the reservoir in a soil which possessed highly diffusive characteristics, the electrical conductivity pattern would more closely approximate the electrical conductivity values in the reservoir. A peak value would be obtained quickly, but values would be expected to drop with time as the concentration of potassium chloride decreased within the reservoir and solute diffused to other locations.

Generally, the graphs in Figure 4.7 display different patterns. One can recall from Chapter 3 and this chapter that all experiments were prepared using similar procedures and that the soil properties were identical between experiments. Therefore, it is believed that differences existing between the graphs were the result of the freeze-thaw history of the soil. The transport properties within the soil were affected by freezing and thawing; however, this alteration is not a simple relationship. To best understand how the freeze-thaw history has changed the diffusive properties of the soil the similarities between experiments will first be examined. The differences between SE and 1FTC, and 1FTC and 3FTC, will then be discussed. Since the probes do not behave identically, conclusions will be based on general trends.

When appropriate, results from pore water extraction measurements displayed in Tables 4.3 to 4.5 will be used to justify conductivity results. Tables 4.3 to 4.5 summarize the percentages of potassium chloride associated with each soil specimen obtained at the end of the experiments. These percentages were then transformed into weights of potassium for the given soil volume represented

Table 4.3 - Final Percentages and Weights of Potassium Chloride for the Structureless Experiment

DEPTH IN BOX	DISTANCE FROM RESERVOIR	PERCENT KCl	WEIGHT OF KCl
10cm	2.5cm	0.72%	4.12g
	5.0cm	0.65%	3.73g
	10.0cm	0.19%	1.45g
	15.0cm	0.03%	0.21g
19cm	2.5cm	0.41%	2.33g
	5.0cm	0.23%	1.33g
	10.0cm	0.04%	0.27g
	15.0cm	0.00%	0.00g

Table 4.4 - Final Percentages and Weights of Potassium Chloride for 1FTC

DEPTH IN BOX	DISTANCE FROM RESERVOIR	PERCENT KCl	WEIGHTS OF KCl
10cm	2.5cm	0.43%	2.46g
	5.0cm	0.27%	1.53g
	10.0cm	0.14%	1.07g
	15.0cm	0.06%	0.43g
19cm	2.5cm	0.39%	2.26g
	5.0cm	0.23%	1.33g
	10.0cm	0.09%	0.70g
	15.0cm	0.01%	0.11g

Table 4.5 - Final Percentages and Weights of Potassium Chloride for 3FTC

DEPTH IN BOX	DISTANCE FROM RESERVOIR	PERCENT KCl	WEIGHTS OF KCl
10cm	2.5cm	0.26%	1.49g
	5.0cm	0.16%	0.93g
	10.0cm	0.13%	0.97g
	15.0cm	0.11%	0.81g
19cm	2.5cm	0.37%	2.14g
	5.0cm	0.21%	1.21g
	10.0cm	0.05%	0.38g
	15.0cm	0.00%	0.00g

by the sampling location (as described in section 3.3.4), which are also displayed in Tables 4.3 to 4.5. There were minimal differences in gravimetric water content and wet bulk density which created a potential error of 0.3% or 0.003g when estimating the weight of potassium chloride. Generally, final weights of potassium chloride correspond with the final conductivity trends for the individual probes. The reader may also recall that these final percentages and weights correspond to the pore water electrical conductivity values used to calibrate the individual probes.

Similarities Among Experiments

From Figure 4.7, there are two major similarities among the experiments. The values at 5cm distances from the reservoir were always lower than the values at 2.5cm distance from the reservoir, and they also reached their individual peaks later. This behaviour would be expected since a greater time was required for potassium chloride to diffuse to 5cm than 2.5cm. In addition, all locations approached equilibrium values by the 25th day. This indicated that diffusion at all probes had slowed to approximate equilibrium values by the end of the experiments. Generally, these similarities between experiments indicate that the probes behaved in a predictable manner for an experiment which did not have a constant concentration source of solute. Therefore, the probes and equipment apparently functioned properly throughout the experiments.

Differences between SE and IFTC

By examining Figure 4.7, three major differences exist between SE and IFTC. First, the time to reach individual peaks for the 2.5cm distances was shorter and the slopes for the lines were greater in IFTC than in SE. In general, this indicates that diffusion occurred at a faster rate in IFTC than in SE at the 2.5cm distance. Freezing and thawing can create fissures and cracks in the soil, that when thawed can increase the permeability of the soil (cf. Chamberlain and Gow, 1978; Chamberlain *et al.*, 1997; Eggington and Dyke, 1990; Eigenbrod, 1996; Othman and Benson, 1993). Increasing the permeability of the soil provides potential avenues for solute diffusion, and thus increase the diffusivity of the soil.

Second, in SE the probes at similar distances from the reservoir generated different results. Towards the end of the experiment, values at the 10cm depth were about twice the value for the similar distance at 19cm depth. This difference is confirmed by the pore water extraction values in Tables 4.3 and 4.4. This result was not expected since the soil conditions should not have been highly different with depth. Some consolidation could have occurred with time during the experiment, but if that did occur, one would expect the peaks to be reached at different times. Since the peak values (for similar distances) were reached at the same time, it appears that the potassium chloride source, driving the concentration gradient, was different at the two depths. If this was so, the reason is unknown at this time. Unlike SE, the probes in IFTC had comparable patterns

of diffusion, which is confirmed in Tables 4.3 and 4.4. Thus, one freeze-thaw cycle affected the two depths similarly, which generated similar diffusivities. Evidence exists (cf. Chamberlain *et al.*, 1997; Othman and Benson, 1993) that freeze-thaw cycles can change the structure of fine-grained soils and that the cryogenic structure becomes more pronounced as the number of freeze-thaw cycles increases. Considering the soil had experienced only one freeze-thaw cycle, and that there was a low clay content in the soil, perhaps the cryogenic structure was not developed enough to create substantial vertical differences.

Furthermore, once IFTC had reached its peak values for the 2.5cm distance from the reservoir, the values began to drop. This did not occur in SE. The drop observed in IFTC could have occurred for a couple of reasons. First, since the rate of diffusion was quite fast in IFTC, the drop observed at the probes could reflect the drop in solute concentration occurring within the reservoir. Sampling of the reservoir at the end of the experiment did indicate that the concentration had dropped from 1% to 0.55%. Also, since the soil had a high diffusivity, potassium chloride after day 10 of the experiment, began to diffuse from this high concentration at the 2.5cm distances to other locations in the soil. The rate of diffusion is believed to be slower in SE since peak values for the 2.5cm distances were reached later and the slopes for their curves were reduced compared to SE, and that is perhaps why the drop in electrical conductivity in IFTC was not observed in SE. Recommended improvements stated in Chapter 5 would attempt to improve the understanding of why the probes at the 2.5cm

distance in 1FTC experienced a drop in electrical conductivity, which was not observed in SE.

Differences Between 1FTC and 3FTC

In Figure 4.7, the trends for 3FTC are different than 1FTC in two major ways. The slopes of the conductivity graphs are much reduced for 3FTC than 1FTC, and it takes the entire length of the experiment (25 days) for the probes in 3FTC to reach their peak. In 1FTC the peak for the 2.5cm probes was reached approximately 6 days after thawing (8 days into the experiment), and 18 days for the 5cm probes (20 days into the experiment). Both of these differences indicate that diffusion was occurring at a much slower rate than in 1FTC. Thus, the diffusivity of the soil must have been reduced by structural changes during the three freeze-thaw cycles. Tables 4.4 and 4.5 also show a reduction in the rate of diffusion for 3FTC in the lower concentrations of potassium chloride at the end of the experiment, compared to 1FTC. Evidence does exist that freeze-thaw can increase the permeability of fine-grained soils (cf. Chamberlain and Gow, 1978; Chamberlain *et al.*, 1997; Eggington and Dyke, 1990; Eigenbrod, 1996; Othman and Benson, 1993), while other evidence has shown that it can also consolidate certain soils (cf. Wong and Haug, 1991). Freezing and thawing may have pushed silt and clay into the pores between individual sand grains. This process would cause soil voids to be 'clogged' by fine textured grains, therefore reducing the rate of diffusion.

Chapter Five

CONCLUSIONS AND SUMMARY

5.1 Introduction

This chapter presents the main conclusions for both the field and laboratory research, and discusses the results with particular reference to the objectives for this research. Additional discussion focuses on recommendations for future research.

5.2 General Conclusions

5.2.1 Field Studies

Drilling solutes exposed to the active layer, due to the upwelling of unfrozen drilling fluids, have moved laterally by into adjoining sediments over the past 20 years up to distances of 10m from sump boundaries. This is a reasonable conclusion when one considers the results from the EM31 survey, soil sample observations, and rough calculations. These contaminants have been concentrated towards the base of the active layer due to solute rejection, water infiltration, and confinement by permafrost. In contrast, no statement about the integrity of drilling contaminants within permafrost can be made since no samples were

obtained below the active layer depth. However, if climate change were to occur, accompanied by active layer deepening, movement of drilling fluids presently in permafrost could transpire, given what has occurred within the present active layer.

5.2.2 Laboratory Experiments

Experiments indicated that freezing and thawing can change the diffusive properties of a sandy loam soil, but the results are not straightforward. The experiment subjected to one freeze-thaw cycle experienced faster diffusion of potassium chloride than a soil which was not subjected to any freeze-thaw cycles. The slope of the graphs for the conductivity probes, at both depths for 2.5cm distance from the reservoir, were steeper than the corresponding graphs for the experiment not subjected to freeze-thaw cycles. Also, less time was required to reach the maximum values for the probes at the 2.5cm distance in the soil exposed to one freeze-thaw cycle, than the experiment exposed to no freeze-thaw cycles. In contrast, the experiment exposed to three freeze-thaw cycles experienced a reduction in diffusion relative to both SE and 1FTC since peak concentrations were not attained until the soil reached equilibrium values at 25 days, and the slope of the curves for all probes was greatly reduced.

5.3 Relation of Results to Objectives

5.3.1 Field Studies

Movement of drilling solutes from sumps can occur over the long term in the active layer if the sides of the sump within the active layer have been exposed to drilling solutes. Concentrations of solutes were not be large (less than 1 percent), and therefore environmental implications at this time would not be of concern. Concern could exist if toxic contaminants were disposed of in this manner since movement can occur over the long term into the relatively unspoiled, fragile environment.

Unfortunately, direct measurements of solute concentrations were not obtained within permafrost. But, if the distribution of permafrost were to change, ie. the sump walls were to thaw, drilling contaminants could be rendered mobile; given the evidence of drilling solute movement within the active layer over the past 20 years.

5.3.2 Laboratory Experiments

It appears that the freezing and thawing history of a soil does affect the transport properties, but for the sandy loam soil used for the experiments, it is not a simple effect. One freeze-thaw cycle improved the diffusive properties when compared to a soil which did not endure freeze-thaw cycling. However, when the number of freeze-thaw cycles was increased to three, the diffusivity of the soil was apparently reduced. Therefore, at contaminant disposal sites in the Canadian

Arctic which have a soil similar in texture to the experimental soil, and have been exposed to multiple freeze-thaw cycles, solute movement by diffusive processes could be reduced.

5.4 Recommendations for Future Research

Improvements for both the field and laboratory studies, which could strengthen future research, are listed below.

Field Research

1) Sampling should include specimens within permafrost outside of the sump boundaries. Therefore, conclusions about drilling solute movement from sumps in permafrost, over the long term, could be made.

2) Additional boreholes should be drilled at a further distance from the sump boundaries to verify the distance to which drilling fluids have moved since the sumps were constructed.

Laboratory Research

1) Soil possessing different textures should be utilized. Therefore, the cryogenic structures would emulate various field situations, which would increase the applicability of the experimental results.

2) Additional conductivity probes should be used to increase the amount of information over the length of the experiment.

3) Increasing the number of pore water extraction sampling locations would improve the detail of diffusion for potassium chloride into each soil container.

4) Microstructure analysis of the soil at and around the probe location would increase the understanding of soil properties influencing the conductivity results.

5) Heave meter(s) should be used to assess if expansion or consolidation of the soil occurred. Expansion would indicate if the soil had developed a significant cryogenic structure or if consolidation of the soil occurred during freeze-thaw cycles.

6) Monitoring of the electrical conductivity of the reservoir would indicate the amount of potassium chloride which had moved into the soil, and thus increase the understanding of its potential influence on the responses at each probe.

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IMAGE EVALUATION TEST TARGET (QA-3)

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