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Evaluation of Freeze Separation as a Treatment for Salt-contaminated Groundwater

by

Steven Lloyd Otto ©

A thesis submitted to the Faculty of Graduate Studies and Research in
partial fulfillment of the requirements for the degree of Master of
Science

in

Geoenvironmental Engineering

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled "Evaluation of Freeze Separation as a Treatment for Salt-contaminated Groundwater" here submitted by Steven Lloyd Otto in partial fulfillment of the requirements for the degree of Master of Science in Geoenvironmental Engineering.

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Dedication

To the ones who supported me from the home front:

Mary, Adam and Beth.

Abstract

Groundwater contamination from road salt infiltration is a common problem at highway maintenance facilities. Freeze separation was investigated as a new application for the ex-situ remediation of groundwater contaminated by road salts. Freeze separation uses natural freezing temperatures to treat groundwater extracted from the contaminated zone, to produce ice and concentrated brine. The ice melts into treated water in the spring, and the brine is removed for off-site disposal.

A literature review and demonstration project confirmed that freeze separation is an effective treatment of contaminated groundwater. The evaluation also resulted in:

- a new method for calculation of concentrations in the ice and brine produced by freeze separation;
- development of a mathematical model to predict the distance that contaminated water will flow across an ice surface during freeze separation;
- a preliminary evaluation process to determine freeze separation viability; and
- cost estimating criteria for future remediation projects.

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The author would like to express sincere gratitude to his supervisors: Dr. Kevin Biggar and Dr. Dave Sego, for their guidance, supervision and encouragement throughout this work, and to Dr. Grant Fisher and Dr. Mary Bourke for their assistance in the development and refinement of the heat exchange model.

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Evaluation of Freeze Separation as a Treatment for Salt-contaminated Groundwater

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Symbol	Description	Units
$A_{surface}$	Area of contaminated groundwater on ground surface	m^2
B	Flowing water film thickness	m
b	Thickness of boundary layer	m
C	Concentration	kg/m^3 or mg/L
C_{allow}	Allowable salt concentration in groundwater after treatment	kg/m^3
C_f	Maximum possible salt concentration in groundwater for a given design temperature T_{air}	kg/m^3 or mg/L
C_{gw}	Average salt concentration in contaminated groundwater	kg/m^3
C_{ice}	Maximum allowable concentration of salt in ice produced by freeze separation treatment	kg/m^3
C_{soil}	Average salt concentration in soil above and below groundwater table	kg/m^3
C'	Reach equation constant	
c_p	Specific heat	J/[kg K]
D_{avg}	Average depth of contaminated zone	m
D_f	Depth of freezing	m
G_r	Grashof number	
g	Gravitational acceleration	9.81 m/s^2
H	Enthalpy	J/kg
h	Convective heat transfer coefficient per unit width	J/[s m^2 K]
h_c	Average convection coefficient of material	J/[s m^2 K]
h_1, h_2	Depth of water in observation well	m
k	Hydraulic conductivity	m/s

k_m	Average convection coefficient of a material	J/[m s K]
k_t	Thermal conductivity	J/[s m K]
L	Latent heat of fusion	J/kg
L_{screen}	Length of well intake area	m
l_s,	Significant length	m
l_{sI}, l_{sII}	Length of flow in heat exchange regimes 1 & 2	m
$\dot{M}$	Mass flow rate per unit width	kg/[s m]
$\dot{M}_{salt}$	Mass flow rate of dissolved salt in groundwater per unit width	kg/[s m]
$\dot{M}_{brine}$	Mass flow rate of groundwater in brine at final concentration per unit width	kg/[s m]
$\dot{M}_r$	Mass flow rate of groundwater removed by ice formation per unit width	kg/[s m]
m_{allow}	Mass of salt that can remain at remediation site	kg
m_{rem}	Mass of salt that must be removed by treatment	kg
m_{soil}	Mass of contaminated soil	kg
m_{tot}	Total mass of salt contamination at remediation site	kg
N_u	Nusselt number	
n_{eff}	Effective porosity	
P_f	Freezing period	s
P_r	Prandtl number	
Q	Flow rate	m^3/s
$q_{conductive}$	Rate of energy loss via conduction per unit width	J/[s m]
$q_{convective}$	Rate of energy loss via convection per unit width	J/[s m]

$q_{specific}$	Rate of specific energy gain per unit width	J/[s m]
q_{tot}	Total rate of latent heat of fusion released by ice formation per unit width (in heat exchange regime 2)	J/[s m]
R	Well reach	m
r_w	Radius of well casing	m
r_1, r_2	Distance from extraction well to observation well	m
s	Well drawdown	ft
T	Temperature	K
T_{air}	Air or design temperature during freezing	K
T_{avg}	Average groundwater temp. in heat exchange regime 1	K
T_{out}	Initial temperature of fluid material or groundwater	K
T_l	Freezing point temperature for the liquid	K
t_1, t_2	Time of measurement for well drawdown test	s
u	Velocity of flow	m/s
v_{brine}	Volume of groundwater that will be removed in brine after treatment	m^3
v_{gw}	Volume of contaminated groundwater	m^3
v_{ice}	Volume of treated groundwater that will remain as ice after treatment	m^3
v_{soil}	Volume of contaminated soil	m^3
v_{tot}	Total volume of groundwater to be extracted for treatment	m^3
v_{total}	Total volume of contaminated groundwater	m^3
Δ	Delta (change in variable)	
ε	Thickness of layer of material added	m

μ	Dynamic viscosity	kg/[m s]
ν	Kinematic viscosity	m^2/s
π	Pi	
ρ	Density of water	kg/m^3
ρ_f	Density of frozen material	kg/m^3
ρ_{soil}	Average density of contaminated soil	kg/m^3

Chapter 1

INTRODUCTION

Groundwater contaminated by road salts used in winter highway maintenance is a widespread problem at most highway maintenance facilities in Alberta, and across Canada (Morin, 2000; TAC, 1999). The contamination is typically widespread and deep beneath the groundwater table from years of persistent point source contamination from salt stockpiles (Morin, 2000). Despite the widespread nature of this problem, there are only a few techniques in common use for site remediation. The two most commonly used remediation techniques, natural attenuation and monitoring, and excavation and disposal off-site of the contaminated soil and groundwater, are often chosen for unit costs more than effectiveness (Snider, 2000). This thesis is an investigation of the suitability of the use of freeze separation as an ex-situ remediation technique for salt contaminated groundwater. Freeze separation has the potential to be an effective alternative to other remediation techniques in common use.

Freeze separation can use natural, environmental freezing conditions to separate dissolved salts from groundwater. The natural mechanism for crystal formation in water results in the preferential separation of water molecules as ice crystals form, with the result that dissolved contaminants are concentrated in the remaining liquid. If freeze separation can be shown to be a valid new treatment option, it could be considered in the evaluation and remediation of the many contaminated sites known to exist in Alberta. The evaluation of freeze separation treatment, described in this thesis, includes development of processes and calculation methods required for the design of a remediation project using freeze separation, including a report on the results of a field demonstration project done in February 2001.

This thesis documents an investigation into the suitability of freeze separation as an ex-situ treatment for salt-contaminated groundwater. Freeze separation, also known as freeze concentration (EPRI, 1987), freeze–thaw conditioning (Jean *et al.*, 1999; Martel, 1999) or freeze crystallization (Suthersan, 1987; Heist, 1981), is the concentration of dissolved contaminants and/or suspended solids in liquids during freezing. It has been used for desalination of brackish surface water (Spyker, 1981; Fertuck, 1968 and 1969; Elmore, 1968) , treatment of wastewater (Martel, 1993 and 1989) and to recover or purify industrial liquid streams (Goa, 1998; Stahl and Sego, 1995; Heist, 1981), and it is reasonable that it would also concentrate salts dissolved in groundwater. While sufficient experimental work was conducted to verify that freeze separation did concentrate groundwater contaminants, the focus of this investigation was on the development of practical guidelines for the application of freeze separation as an ex-situ groundwater remediation technique.

1.1 Organization of the thesis

This thesis has three general sections:

1. Chapters 2 through 4 discuss the use of road salts, previous uses of freeze separation, and design considerations for the application of freeze separation,

2. Chapter 5 describes the field project conducted to demonstrate the use of freeze separation as a remediation technique, and
3. Chapters 6 and 7 contain analysis techniques and information required to evaluate the use of freeze separation at a particular site.

Chapters 4, 6 and 7 contain the core knowledge required to determine the suitability of freeze separation as a possible remediation treatment, and for detailed planning of a remediation project using freeze separation.

Chapter 2

THE ENVIRONMENTAL RISK FROM ROAD SALTS

2.1 Introduction

This chapter outlines the current practice and environmental impacts of the use of road salts for winter highway maintenance. Section 2.2 is a description of the family of chemicals known as road salts. In section 2.3 the current practices for the use of road salts by Alberta Transportation are summarized. Section 2.4 summarizes the environmental consequences of the continued use of road salts, with an emphasis on groundwater contamination. Section 2.5 gives examples of benefit/cost analyses for the continued use of road salts. Unless otherwise noted, all information in this chapter is from the Transportation Association of Canada Road Salt Management Guide (1999).

2.2 Road salts

Road salts are a family of chemicals used in winter highway maintenance. These salts include sodium chloride, calcium chloride, magnesium chloride, calcium magnesium acetate, potassium chloride, potassium acetate, sodium acetate, or combinations of these salts. By far the most commonly used road salt in North America is sodium chloride, due to the abundance of natural supplies, preferred handling characteristics and low cost. In Western Canada, most sodium chloride for road salts is produced as a byproduct of potash production in Saskatchewan.

Sodium chloride may have ferric ferrocyanide or sodium ferrocyanide added at 30 to 124 mg/kg as an anti-caking agent, depending on the supplier (Environment Canada & Health Canada, 2000). While ferrocyanide is stable and low in toxicity in the absence of direct sunlight, various species of cyanide has been observed as a contaminant in the groundwater at some salt-contaminated sites.

2.3 Road salt usage

Road salts have been used in North America to clear highway surfaces of snow and ice since the late 1930s (Hogan, 2001), either as an application of straight salt or mixed with other abrasives (i.e., sand). Approximately five million tonnes of sodium chloride are used annually on Canadian roads, with the heaviest applications in the provinces of Ontario and Quebec (Environment Canada & Health Canada, 2000). The provincial government in Alberta uses about 130,000 tonnes annually (Snider, 2000).

The practice of highway maintenance by Alberta Transportation has been to apply salt, or salt mixed with sand, to icy or snow covered paved highways as necessary throughout the year. Application rates are selected according to pavement conditions; ranging from 50 kg/km of salt alone applied to slightly icy pavements at temperatures close to freezing, to over 800 kg/km for various salt and sand mixtures applied to packed snow or ice at very cold temperatures (Alberta Transportation, 2000).

Road salts are spread onto pavements to form a salt brine that prevents the formation of a bond between the road surface and snow and/or ice cover, or to destroy a bond which has become established. Where the snow or ice cover is not bonded to the pavement, it can be broken up and removed easily by plowing or under normal wheel loading of traffic. Sand is spread over icy or snow covered pavements to increase the frictional resistance between the pavement surface and tires. Sand used for winter maintenance is mixed with a road salt to "freeze-proof" or "pickle" the sand stockpile during the winter. The two most common de-icing chemicals used by Alberta Transportation are crystalline sodium chloride (mixed with sand at 5 to 10% by volume), and 35% flake equivalent liquid calcium chloride (mixed with sand at 0.5 to 1% by weight) (Alberta Transportation, 2000).

Road salts in Alberta are normally stored in a dedicated structure at a highway maintenance facility, to minimize losses from precipitation and wind. Sand used for highway maintenance is predominantly stored in outdoor stockpiles without any protection from rain, snow or wind. The few covered sand stockpiles are in special storage structures that are justified because the maintenance facility is adjacent to environmentally sensitive areas, or surrounded by residences. Road salts are lost to the surroundings by leaching from sand stockpiles or from dissolved salts spilled during handling near the salt shed. Most highway maintenance facilities have been in place since the 1970s, and as a result there has been continual leaching of dissolved salt into the soil and groundwater over many years at these locations (Snider, 2000). Environmental site assessments conducted between 1995 and 1998 on highway maintenance facilities showed that the overwhelming majority of stockpile sites have well developed, deep contamination that extends well below the groundwater surface (Bowker, 2000). This characteristic of contamination at highway maintenance facilities reduces the effectiveness of the two most commonly used remediation methods: remediation by natural attenuation or excavation and landfill disposal (Bowker, 2000). At publicly owned properties, the cost of treatment can be a more important factor than the time required for remediation (Snider, 2000). Adams (1995) discusses how the allowable degree of uncertainty about actual site conditions can be managed by evaluation of the cost effectiveness of the various techniques being considered; in the case of highway maintenance facilities where there may not be any particular urgency to complete remediation, and a lower cost remediation treatment over several months or years may be the preferred option.

2.4 Environmental risks associated with the use of road salts

The environmental impacts of salt contamination in Canada have been a concern since the 1980s. Jones *et al.*. (1986) provides a comprehensive survey of environmental impacts from the use of road salts in Ontario. Morin (2000) is a more recent summary of case studies from across Canada showing the environmental impacts of road salt use. Both references indicate that groundwater contamination from road salts is a wide-spread problem for all levels of government in all parts of the country.

Road salts enter the environment by:

- Road salts are applied to the pavement before, during or after snow or ice accumulates.

- The salts crystals absorb water and form a brine solution on the road surface. In rare cases, not all crystals will have dissolved before being plowed from the highway surface.
- Some salt remains on the surface, dries, and is transported by vehicle – induced turbulence or by the wind as particulates onto the vegetation, soil or aquatic features adjacent to the roads.
- Salt brine droplets are blown as a spray onto soil or vegetation adjacent to the road. These droplets may infiltrate the soil to enter the groundwater, be taken up by vegetation, or physically coat the vegetation. The finest droplets of salt brine spray may be transported long distances from the road surface.
- Salt brine drains from the pavement into the soil adjacent to the highway, or is transported as run-off into watercourses.

Once road salts enter surface waters, they may induce behavioral changes or mortality in aquatic species through changes to density–dependent ecological processes or mobilization of contaminants from bottom sediments (TAC, 1999).

Dissolved road salts enter the soil and affect the soil structure, permeability and plant fertility rates (TAC, 1999). Calcium and magnesium ions in the soil can be replaced by sodium ions, particularly in soils with high clay or organic content. As sodium replaces calcium or magnesium, the soil pH increases and soil particles disperse. This often results in decreased soil permeability and aeration. Salt concentrations as low as 100 mg/L can damage some species of vegetation by desiccation, due to change in osmotic pressure gradient in the soil solution (TAC, 1999). Dissolved salts that enter the groundwater can impact local water use through elevated concentration of sodium or chlorides, by an increase in groundwater hardness, or by mobilization of trace metals from the soil. Groundwater contaminated by road salts has been reported to depths in excess of 130 metres, and having traveled more than 1,700 m horizontally in less than 20 years (Morin, 2000).

All of these environmental pathways are also applicable to salt lost from maintenance facilities. Road salts may spill from the storage shed during loading or fall from loaded plow trucks. Exposed pickled sand stockpiles left over from the previous winter can lose more than 50% of their contained salt in a single summer (New Brunswick Department of the Environment, 1978), as the salt leaches from the stockpile into the surrounding soil.

Individual foremen at maintenance facility have been historically responsible for cleaning up spills and maintaining the condition of local surface drainage structures. Not all foremen were equally concerned about following good housekeeping practices, so the amount of salt contamination varies from location to location (Bowker, 2000). There are at least 120 sites where the Alberta government has stockpiled road salts or pickled sand, and all have some degree of salt contamination. Municipal, county, village and federal governments also operate maintenance facilities, so a conservative estimate is that there are at least two hundred and fifty salt contaminated sites in the province of Alberta (Snider, 2000). Site investigations have found salt contamination ranging from slight surface contamination to contaminated soil zones that extend more than fifteen meters below the groundwater table; and in concentrations of up to 60,000 mg/L (Snider, 2000). Of the 120 provincially owned sites, concentrations of salt contamination of local groundwater exceed provincial surface water quality limits (maximum 230 mg/L for chlorides) in all but one location. Remediation efforts for salt contamination are underway as budgets allow, prioritized according to the extent of off-site damage being reported by adjacent landowners.

2.5 Benefits and direct cost from use of road salts

Most of Canada, and all of Alberta, require some degree of winter highway maintenance to ensure that roads are generally safe for use by private, commercial and emergency service vehicles. The benefits from winter highway maintenance for safe winter travel include:

- fewer accidents,
- improved travel time,
- reduced travel costs,
- improved economic productivity,
- opportunity to engage in social activities,
- provision of emergency services, and
- reductions in accident claims (although the overall minor injury accident rate is higher during winter conditions, the serious injury accident rate is lower on maintained roads than on un-maintained roads).

European traffic safety research has concluding that the rate of injury accidents is reduced an average of 20% through the use of road salts to de-ice the road surface (TAC, 1999). The Insurance Corporation of British Columbia (ICBC) conducted an anti-icing pilot project in Kamloops that found that the use of road salts was a cost effective method of reducing accident rates. As a result, ICBC reimburses the capital costs for implementation of anti-icing technology by private maintenance contractors province-wide in order to receive the indirect benefits of lower motor vehicle insurance claims (ICBC, 2001).

The costs from the use of road salts include:

- direct material and operating costs of highway maintenance;
- the cost to human health (particularly to the population sensitive to elevated salt concentrations in drinking water);
- the cost to the environment (i.e., chloride injury to roadside vegetation, sodium accumulation in soils, and increased salinity in surface and ground waters);
- the cost to the road infrastructure (i.e., accelerated oxidation of structural and reinforcing steel in bridges, utility poles and other structures); and
- the cost to vehicle owners of salt corrosion.

Studies since 1991 have found that there is a positive benefit/cost ratio for the use of road salts of between 2.0 and 6.5 to 1, depending on the type of highway and traffic volumes being considered (TAC, 1999). In Canada, all provincial highway agencies and Environment Canada agree that there are significant costs associated with the use of road salts, but the benefits from salt use is great enough that there is little chance that there will be a significant reduction in salt use in the foreseeable future (TAC, 1999).

Chapter 3

PREVIOUS USE OF FREEZE SEPARATION

3.1 Introduction

No published reports of the use of freeze separation for the ex-situ treatment of contaminated groundwater were found. Freeze concentration is listed by Knox *et al.*. (1986) as a treatment method in a table titled "Other Treatment Techniques for Inorganics" in the chapter titled "Treatment of Groundwater". However, the source for the table in Knox *et al.*. is Patterson (1978), which referred only to treatment of cadmium and chromium industrial wastes, and did not refer to treatment of groundwater.

3.2 Previous applications of freeze separation treatment

The conceptual model of freeze separation has been improved by the work of Harrison and Tiller (1962) and Martel (1999). Natural freeze separation produces fresh water from sea ice, and has been a source of drinking water from pre-history in cold regions. Research for industrial scale freeze separation of sea water began in the 1950s, but there has been limited full-scale application. Elmore (1968) showed that freeze separation by spray freezing can produce drinking water from brackish groundwater on an economic scale, and work by Fertuck (1968, 1969) and Spyker (1981) at the Saskatchewan Research Council expanded on Elmore's research between the late 1960s through the early 1980s. C. J. Martel has conducted a series of experiments at the United States Army Cold Regions Research and Engineering Laboratories for the use of freeze separation as a treatment of municipal waste water containing suspended solids between the early 1980s through the present (Martel, 1989 and 1993). Of particular importance in Martel's research was his development of a predictive model for the depth of ice formation in any given climate, which is one of the limiting factors in the design of a freeze separation remediation treatment plan (Martel, 1989).

Many other researchers have investigated the use of natural freezing to de-water sludges and separate liquids and solids from industrial or municipal wastes:

- Heist (1981) for cooling tower blowdown and pickle liquor,
- Stahl and Sego (1995) for mine tailings,
- Gao (1998) for pulp mill effluent, hog processing wastewater and oil sands tailing,
- Alberta Agriculture, Food & Rural Development (1999a & b) for food processing and hog manure waste waters,
- Jean *et al.*. (1999) for oily sludges from petroleum refining, and
- Parker *et al.*. (2000) for municipal wastewater.

These references show that freeze separation is an effective method for the concentration of dissolves substances and suspended particles, and by extension it should be an effective ex-situ treatment of contaminated groundwater. The effectiveness of freeze separation as a treatment for road salts in groundwater will be influenced by concentrations of the salts involved and climatic conditions. Experimental results have shown that solutions of monovalent ions have greater freeze separation than solutions with di- or multi- valent ions (Elmore, 1968; Spyker, 1981). Elmore (1968) identifies sodium chloride, potassium chloride and calcium chloride as dissolved contaminants that will have a high percentage removal using freeze separation (in the range of 95 to 97% removal). Other contaminants, such as magnesium carbonate, calcium carbonate, calcium bicarbonate and magnesium bicarbonate, will have a lower percentage removal from freeze separation.

Research into freezing patterns of seawater has shown that sodium chloride, magnesium chloride and sodium sulfate are all concentrated by freeze separation (Pounder, 1969). Harrison and Tiller (1962) have shown that the process of crystal formation, the driving mechanism of freeze separation, is consistent in most aqueous solutions. From this, it is a logical conclusion that freeze separation will concentrate all types of dissolved road salts to various degrees of efficiency, with the best results for the road salts most commonly used: sodium chloride and calcium chloride.

Following in this thesis are discussions of the factors that must be considered for the design of a remediation project using freeze separation, a report on a demonstration project that showed the effectiveness of freeze separation, and the development of cost estimating and treatment evaluation tools.

Chapter 4

DESIGN FACTORS FOR FREEZE SEPARATION TREATMENT

4.1 Introduction

As discussed in Martel (1993) and Grant (2000), much of the Northern Hemisphere has a climatic that provides reliable natural freezing for several months of each year, and the climatic potential exists for use of ex-situ freeze separation in most of Canada. It is a trivial deduction that areas that are cold enough to support treatment by freeze separation are also the areas that are likely to have problems with groundwater contamination from road salts.

The theory behind freeze separation is simple and elegant: as ice crystals grow in water, the crystal structure preferentially forms from water molecules to the exclusion of dissolved chemicals or suspended solids. Under ideal conditions the resulting ice is composed of pure water, and the remaining solution contains the concentrated contaminants. Complicating effects are changes in temperature which affect the rate of ice formation, the amount of mechanical mixing, fluid film thickness, and the pathway that the brine follows as the crystal front advances. In real conditions these complicating factors result in brine pockets and micro-channels in the ice mass, where the local concentration of salts is higher than in the surrounding ice. Pounder (1969) discusses how these pockets of immobilized contaminant may form preferential drainage pathways as the ice mass begins to melt. The meltwater collected during the first stages of melting contains a significant amount of the total salt mass in the ice, and capture of this initial meltwater will increase the effectiveness of freeze separation treatment. Fertuck (1969) noted that in an ice mound formed by spray freezing, ice in the top 300 mm consistently had a lower concentration of contaminants than ice lower in the mass; he concluded that this was due to the change of orientation in ice crystals and the subsequent formation of meltwater channels. Elmore (1968) noted that re-crystallization of ice crystals over time will produce higher permeability, with subsequent migration of immobilized salts to the crystal boundaries where it can be washed out of the ice mass with the first meltwater in the spring.

The remainder of this chapter introduces the factors to be considered when designing and planning the use of freeze separation as a remediation treatment of contaminated groundwater. The rest of section 4.1 contains an overview of extraction of contaminated groundwater for ex-situ treatment, popularly known as "pump and treat", and a summary of the regulatory requirements for remediation of salt contaminated groundwater in Alberta at the time of publication.

Section 4.2 discusses the types of information available to the remediation planner following a comprehensive site assessment, and the additional information that will be required for design of the remediation project. Sections 4.3 show the calculations used for determining the volume of contaminated groundwater to be treated and the pumping rate. Section 4.4 gives a method to calculate the maximum thickness of ice that may be formed during treatment. Some considerations that are unique to remediation by freeze separation at a particular site are outlined in section 4.5. In section 4.6, a mathematical model is developed for the flow of contaminated groundwater as a thin sheet across an ice surface. The distance that the groundwater will flow during freeze separation in this manner can be used in design of the retaining pond.

An assumption taken in this chapter is that the contaminated groundwater is contained in an unconfined aquifer. The references given also contain appropriate theory that could be used to plan for remediation of contaminated groundwater in a confined aquifer.

A proposed sequence for design of freeze separation treatment is:

1. Collection of site data from environmental site assessments (ESAs).
2. Determine if freeze separation is a viable remediation treatment option at the site.
3. Field testing to determine other necessary parameters as required (for example, hydraulic conductivity or porosity)
4. Determine the total volume of contaminated groundwater, mass of dissolved salts, pumping rate, recharge rates for the contaminated aquifer, background flow conditions, the concentration of effluent brine produced by freeze separation, average concentration of salts in the ice produced by treatment, and the air temperature required for successful treatment.
5. Design of the extraction system – pumps, tubing, location of extraction wells, etc.
6. Design of above-ground infrastructure – pump controls, retaining ponds, equipment storage, etc.
7. Design of the remediation sampling and testing programs

Concurrent with these steps is application for the necessary permits and approval for the remediation project.

4.1.1 Overview of pump and treat remediation

Extraction of groundwater for ex-situ remediation, commonly referred to as pump and treat, has had limited success in generating the desired reduction in contaminant concentrations. A variety of factors all contribute to difficulties experienced with this strategy, including (Keely, 1996):

- variations in groundwater flow (velocity and direction) produced by extraction,
- inadequate consideration of natural flowlines that are characterized by tortuosity and heterogeneity,
- inadequate understanding of soil conditions,
- inadequate understanding of the distribution and chemical properties of the contaminant,
- inadequate understanding of soil /contaminant /groundwater interactions,
- failure to modify the conceptual and contaminant transport models to reflect the effect of groundwater extraction,
- inadequate modification of the treatment and monitoring plans during operation to adjust for changing conditions, and
- unrealistic goals for contaminant removal, time required or costs.

Adams (1995) outlines many of the difficulties encountered when determining hydrologic and geotechnical parameters needed for planning pump and treat projects, along with a review of methodologies that could improve the possibility of successful pump and treat projects. Many pump and treat remediation projects since the late 1970s have been for the treatment of hydrocarbons, chlorinated solvents or halogenated aliphatic compounds. The complex chemical nature of these contaminants, and their sorption onto soil particles or residuals entrapped in the soil matrix, have contributed to the relatively low success rate of pump and treat remediation projects (Adams, 1995). In contrast, road salts are non-reactive at typical concentrations, are readily transported by groundwater flow, and have relatively high regulatory limits (discussed further in Section 4.1.2). The use of pump and treat remediation for salt contamination can still encounter difficulties with groundwater extraction as a result of:

- the formation of stagnant zones in the aquifer from disruption of the natural hydrologic flow,
- contaminated groundwater immobilized above the water table, or
- areas with restricted groundwater removal due to pockets of soils with lower hydraulic conductivity.

A factor that will mitigate these difficulties is that the allowable concentration limits for road salts is typically several orders of magnitude higher than for organic contaminants. For these reasons, pump and treat has the potential to be more successful in remediation of salt contamination of groundwater than for treatment of other contaminants.

4.1.2 Regulatory goals for contaminant concentration in treated groundwater

Canadian drinking water guidelines (Federal – Provincial Subcommittee on Drinking Water, 1999) give guidelines for allowable concentrations of road salts as dissolved constituent ions. Table 4.1 shows the guidelines for ions created in aqueous form from commonly used road salts. Surface water quality guidelines in Alberta (Alberta Environment, 1999) give allowable concentrations for road salt constituents as shown in Table 4.2. Alberta Environment has also published guidelines for reclamation of oil sand leases (Oil Sands Wetlands Working Group, 2000) that have fresh water wetland salinity class guidelines as shown in Table 4.3.

The Government of the Province of Alberta has published salt contamination assessment and remediation guidelines (Alberta Environment, 2001) which apply to remediation projects in the province. In November 2001, Environment Canada and Health Canada announced that road salts will be added to the Canadian Environmental Protection Act's Priority Substances List 1 (Environment Canada, 2001). The announcement says that the current use of road salts can have a demonstrable influence on vegetation and aquatic species adjacent to highways or storage sites; but does not claim that road salts are toxic to humans. At the time of publication, the consequences of this declaration are not known, but it is expected that there will be a multi-year implementation period where new regulations concerning storage, handling, monitoring and application of road salts are introduced. The announcement that road salts will be listed as an environmentally toxic substance has increased the priority for the remediation of salt contaminated sites (Snider, 2000). Most provincial and municipal transportation agencies had anticipated the declaration by introducing improved storage procedures, using reduced application rates and the introduction of state-of-the-art weather forecasting. A further consequence of declaring road salts an environmentally toxic substance may be that regulatory limits for allowable salt concentration in surface waters or groundwater will decrease to near drinking-water standards.

4.2 Typical information available from Phase II and Phase III environmental site assessments

The selection of a remediation process should be done after sufficient site investigation has been completed to establish the limits of the contaminated zone (CCME, 1997). This usually involves at least a Phase III ESA. Alternately, freeze separation may be one of the remediation options proposed as part of a Phase III ESA.

At the completion of typical Phase I and II ESA, the designer should know (CCME 1997):

- general geologic features,
- local hydrology, including precipitation and surface drainage patterns,
- information on the source and nature of contamination,
- an initial conceptual model of the hydrogeological system,
- identify potential problems related to health, safety and site access,
- relative thickness and location of major stratigraphic soil units from borehole logs,
- mineralogy and sediment or rock type present,

- soil parameters (i.e., grain size distribution, plasticity, porosity, permeability and degree of saturation),
- groundwater level for each borehole,
- hydraulic gradient across the site,
- concentration of contaminants within the contaminated zone and at background levels from disturbed samples taken at the site,
- the extent of the contaminated area, from interpolation of borehole logs or by surface geophysical testing, and
- the regulatory or site specific contaminant concentrations that must be achieved for successful remediation.

At the completion of a typical Phase III site ESA, the designer should have (CCME 1997):

- a detailed knowledge of the hydrogeological system,
- all data needed for quantitative analysis of groundwater flow system (including the hydraulic gradient and direction of groundwater flow), and
- a developed system of test and monitoring wells, some of which may be suitable for extraction of contaminated groundwater

Two parameters that are often not presented in Phase II and III ESAs are:

- porosity, or effective porosity, for the various soil strata, and
- hydraulic conductivity across the site.

Porosity, or effective porosity, may be estimated or determined by laboratory testing of a undisturbed soil sample. Table 4.4 gives typical values of porosity for several aquifer soil types. Effective porosity is usually less than porosity (CCME, 1994). A reasonable estimate of porosity is often possible from the initial drilling and soil sampling program (CCME, 1994).

While hydraulic conductivity can be found from laboratory testing of undisturbed samples, the remediation planner is apt to be more interested in the effective hydraulic conductivity and variation within the site determined by on-site well tests. It will be cost effective if the design of test holes and monitoring wells necessary for a Phase III ESA include at least one set of wells suitable for well tests. In order to undertake hydraulic conductivity tests using measurement in adjacent wells, the designer must ensure that the observation wells will respond to pumping from the extraction well. An estimation of the reach of the extraction well, defined as the maximum radius of a circle beyond which the well has no significant influence on the original groundwater level, was proposed by Sichardt as (Leonards, 1962):

$$R = C's\sqrt{k} \qquad [4.1]$$

where: R = reach of the well (feet),
C' = a constant, given by Sichardt as 3.0 and later by the U.S. Army Corps of Engineers as 1.5 to 2.0,
s = drawdown from original piezometric surface (feet), and
k = hydraulic conductivity (cm/s)

Note that this formula was developed in a combination of Imperial and metric units, and the constant value C' carries a 'hidden' unit conversion value. For an initial calculation of well reach, the remediation designer could assume a value for the hydraulic conductivity based on soil types identified at the project site.

Hydraulic conductivity can be calculated for steady state radial flow in an unconfined aquifer as (Todd, 1980):

$$Q = \pi k \left(\frac{h_2^2 - h_1^2}{\ln\left(\frac{r_2}{r_1}\right)} \right) \qquad [4.2]$$

where: Q = flow rate (m^3/s),
k = hydraulic conductivity (m/s),
h_1 = depth of water in observation well 1 (m),
h_2 = depth of water in observation well 2 (m),
r_1 = distance from extraction well to observation well 1 (m), and
r_2 = distance from extraction well to observation well 2 (m).

The relationship between the parameters in equation [4.2] is shown in Figure 4.1. Note that Figure 4.1 shows the three wells in a 2-dimensional linear configuration; in practice the wells can be in any configuration. This equation is applicable to steady state flow so long as the Dupuit assumptions of a fully penetrating well, instantaneous and infinite recharge in horizontal flow and infinite, horizontal strata are valid. As the drawdown increases, the Dupuit assumptions become invalid either from non-horizontal flow or lack of reacharge, and pumping tests to determine hydraulic conductivity should be done at extraction rates small enough that drawdown is small in comparison to the saturated thickness of the aquifer (Todd, 1980).

The investigator may choose to conduct a single well drawdown test to estimate the hydraulic conductivity. Several methods of interpretation of pressure recovery measurement are summarized in Domenico and Schwartz (1990). A commonly used method where the well screen intake length is greater than eight times the radius of the well was developed by Hvorslev in 1951 as (Domenico and Schwartz, 1990):

$$k = \frac{r_w^{\,2} \ln\left(L_{screen} / r_w\right)}{2\,L_{screeen}} \left(\frac{\ln\left(h_1 / h_2\right)}{\left(t_2 - t_1\right)} \right) \qquad [4.3]$$

where: k = hydraulic conductivity (m/s)
t_1 = time of measurement number 1(s),
t_2 = time of measurement number 2 (s),
h_1 = depth of water in well at time t_1 (m),
h_2 = depth of water in well at time t_2 (m),
r_w = radius of the borehole or well casing (m), and
L_{screen} = length of the well intake area (m)

Figure 4.2 shows how these variables relate to each other. The remediation planner must be aware of the possibility of preferential flow, from fractures or heterogeneity, that will simultaneously increase the effective hydraulic conductivity and reduce the effectiveness of extraction of the contaminated groundwater (CCME, 1996).

4.3 Calculation of the volume of contaminated groundwater

A simple method to estimate the volume of contaminated groundwater is (Roscoe Moss Company, 1990):

$$V_{total} = A_{surface}\, D_{avg}\, n_{eff} \qquad [4.4]$$

where: V_{total} = total volume of contaminated groundwater (m^3)
$A_{surface}$ = area of contamination on ground surface (m^2),
D_{avg} = average depth of contaminated zone (m), and
n_{eff} = effective porosity (dimensionless)

If effective porosity was not determined previously, it may be estimated from porosity and consideration of the soil type and geologic history at the site.

The minimum pumping rate for a freeze separation remediation project can be calculated from the number of days of freezing temperatures, taken from climatic data, compared to the total volume of water that is to be extracted for treatment. The total volume of water to be extracted may be several times the actual volume of contaminated groundwater. Under ideal soil conditions of a saturated, uniform aquifer, only the actual volume of contaminated water would need to be extracted and treated. Real soil conditions, such as preferential flow paths and less permeable lenses or strata, will require a greater volume of groundwater be removed in order to "flush" the entire contaminated zone. As previously discussed in section 4.1, it may not be necessary to remove all of the contaminating salts in order to achieve the remediation goals. The remediation planner will have to choose the total quantity of contaminated groundwater to be removed based on engineering judgment of site hydrology, contaminant history and the length of time available for remediation.

Equation [4.2] can be used to calculate flow rate once the hydraulic conductivity is known. The remediation planner should calculate the actual pumping rate based on the desired cone of depression. The majority of the contaminated zone should remain below the cone of depression (i.e., the phreatic surface), since some contaminated groundwater may be held immobile by capillary forces in the unsaturated zone. Figure 4.3 below shows an idealized steady state pumping condition.

In certain conditions, the contaminated zone may be highly concentrated and the necessary amount of contaminated groundwater could be removed under unsteady flow conditions. In that case, the flow rate may be greater and the final location of the cone of depression can be below the upper surface of the contaminated zone.

4.4 Calculation of maximum ice mass thickness

Following extraction, groundwater can be:

- sprayed through the air and freeze as airborne droplets,
- pumped into the retaining structure and freeze in a mass that floats above the liquid body (i.e., natural ice formation on ponds), or
- spread over an existing ice surface as a thin film to freeze and accumulate in thin sheets of ice.

Regardless of how the groundwater is handled after extraction, it will form an ice mass plus effluent brine which contains elevated concentrations of contaminant. For freeze separation treatment by spraying into the air, Gao (1998) advised using the equation developed by Martel (1989) to plan the maximum thickness of ice mass that will melt naturally during the subsequent summer. Martel had developed his equation for the total thickness formed by freezing of thin layers of sludge and waste water above an existing ice surface. The equation for the maximum thickness of ice formed is (Martel, 1989):

$$D_f = \frac{P_f (T_{out} - T_{air})}{\rho_f L \left(\frac{1}{h_c} + \frac{\varepsilon}{2 k_m} \right)} \qquad [4.5]$$

where: D_f = depth of freezing (m),
P_f = freezing period (s),
T_{out} = initial temperature of the fluid material (K),
T_{air} = air temperature during freezing (K),
ρ_f = density of frozen material (kg/m^3),
L = latent heat of fusion (J/kg),
h_c = average convection coefficient of material (J/[s m^2 K]),
k_m = thermal conductivity of material (J/[m s K]), and
ε = thickness of layer of material added (m)

Martel (1993) suggests values for wastewater treatment using equation [4.5] as:

P_f = site specific, from meteorological records (s),
T_{out} = 273 K,
T_{air} = site specific, from meteorological records (K),
ρ_f = 917 kg/m^3 (waste water) {999.87 kg/m^3 for water in Weast, 1973},
L = $0.235 * 10^6$ J/kg {$0.335 * 10^6$ J/kg in Taylor, 1973},
h_c = 7.5 J/[s m^2 K],
k_m = 2.21 J/[m s K], and
ε = minimum 0.05 m, there is no maximum but freezing rate will decrease as ε increases

Note that the parameter (k_m) named by Martel as the average convection coefficient of material is defined in Kinsky (1977) as the overall heat transfer coefficient, equal to the thermal conductivity divided by the thickness of the material that the heat is flowing through. Using Martel's wastewater layer thickness of 0.05 m results in a thermal conductivity for wastewater with suspended solids of 0.375 J/[m s K]. The value of thermal conductivity for water from Kinsky (1977) is 0.522 J/[m s K] for water at 0 °C, which is similar to the implied value used by Martel.

Equation [4.5] will give the maximum depth of freezing that can be accomplished. By using variable T_{air} as the average temperature during the months of above freezing temperature and the value of ε as the total thickness of the ice mass, the depth of thawing can also be calculated. Obviously, where the annual thawing depth is less than the freezing depth, the maximum thickness of ice mass that should be produced is the thawing depth, in order to prevent annual buildup of ice.

The finite difference model to predict the thickness of ice produced above a body of saline water developed by Fertuck (1968) could be used instead of equation 4.5 under the appropriate conditions. This model assumes that the ice can be divided into at least two layers with uniform temperature change over depth, and the ice is not snow covered.

4.5 Site-specific considerations

It is an axiom that conditions at every remediation site are unique. At the conclusion of the ESAs, most of the necessary information needed for the initial conceptual model will have been gathered. Adams (1995) makes a strong case for using an observational approach to design and implementation of remediation by 'pump and treat'. The observational approach, which incorporates feedback and validation of the conceptual model through monitoring of actual conditions as the remediation project progresses, offers the greatest potential for maximum efficiency of extraction of the contaminated groundwater for treatment. The following sections discuss other "above ground" factors that will affect the effectiveness of treatment by freeze separation.

4.5.1 Size and location of retaining ponds

The shape of the property available for the remediation project can influence the shape and location of the retaining pond(s). The distance from the extraction well to the retaining pond may require that the above-ground plumbing be insulated or heated to prevent the groundwater from freezing in the pipe before it reaches the pond. The bottom of the pond should be nearly level, with a low point that can be used to collect effluent brine. In some cases, remediation may be take place on a site where highway maintenance work is still in progress, and the designer will have to adjust his layout to accommodate the actions of the highway maintenance crew.

The size of retaining ponds will depend on the volume of contaminated groundwater that will be extracted during each winter cycle. Work carried out by the Saskatchewan Research Council (Fertuck, 1968) has shown the necessity of impermeable liners to prevent brine leaching from the retaining pond. The cost of a geomembrane pond liner may very well exceed the cost of excavating the pond, and the designer is advised to consult with the geomembrane supplier to find the most cost effective pond shape. There are two basic methods for retaining pond construction: excavation, or above-ground. Excavation should be considered if the earthwork will not interfere with subsurface flow or extraction of the groundwater. Above-ground ponds can be constructed with berms of native soil or material brought to the site, and can be constructed at any time of the year. Above-ground retaining ponds involve only minor earthwork, and can be constructed or removed easily with light equipment (i.e., front end loader and gravel trucks).

4.5.2 Location of extraction and observation wells

The traditional method of groundwater extraction is to place the extraction well into the most heavily contaminated zone. On sites where highway maintenance work is still in progress, this may not be possible, and the designer may want to plan for horizontal drilling into the contaminated zone to avoid obstruction of normal site operations. The extent of the contaminant plume will ultimately determine the number and placement of extraction wells. Monitoring wells should be installed at the same time as the extraction wells; the sampling wells installed during the ESA may be suitable for some of the monitoring and extraction wells. In some cases, the location of the contaminant plume may require some extraction or monitoring wells be placed on adjacent properties.

4.5.3 Assessment of the need for covered retaining ponds

Natural precipitation (snow or rain) may occur during a freeze separation project. Snow cover on the surface of ice in a retaining pond will decrease the rate of heat loss to the air, and inhibit the rate of ice formation (Ashton, 1980). Fertuck (1968) discussed how snow cover on natural ponds slowed the rate of ice formation; this resulted in a smaller quantity of ice with a lower effluent brine concentration. Martel's equation for maximum depth of ice formation (equation [4.5], discussed in Section 4.4) assumes no snow cover on the ice surface. Large enough quantities of snow could fall or drift into a retaining pond that the total volume of extracted water and precipitation exceeds the pond's capacity. The designer needs to balance the capital cost of placing a cover over the retaining pond(s) to the reduced effectiveness produced by the factors described above.

4.5.4 Effluent brine concentration, monitoring freeze separation treatments and re-cycling effluent brine

The maximum concentration of dissolved salts is a function of the ambient temperature, as described by the phase diagram for the salt - water system. The simplest case is one salt in pure water, as shown graphically in Figure 4.4 and in Table 4.5 for sodium chloride and water. The actual phase diagram for groundwater from the contaminated site will be similar to Figure 4.4, with differences from the effects on equilibrium phase concentrations of the mixture of road salts and naturally occurring groundwater ions. Taken from Figure 4.4, Table 4.5 gives the theoretical maximum concentration possible at a given air temperature, for a 2-phase system of sodium chloride brine and pure ice. Since air temperature varies during the day, and the concentration of brine produced will vary as air temperature varies, a conservative design will use the average maximum daily temperature.

As noted in Section 4.1.2, the regulatory allowable limits for concentration of road salt are in the order of 5,000 mg/L or less, depending on the future use of the water. In Morin (2000), the range of concentrations reported for groundwater contaminated by road salts varies widely between sites, but is generally at a concentration of less than 100,000 mg/L. The remediation planner who intends to use freeze separation must be able to predict the conditions necessary for successful treatment, and implement a system of monitoring to ensure that the treatment is meeting these conditions. The total mass of salt contamination includes road salts dissolved in mobile groundwater, road salts dissolved in immobile groundwater (i.e., in immobile pore spaces or within the boundary layer of clay particles) and dissolved road salts immobilized above the groundwater table. See Figure 4.5 for a conceptual diagram of freeze separation of the extracted groundwater. Only those road salts in mobile groundwater are available for extraction and treatment. The following paragraphs outline a method of calculation of concentrations and volumes of ice and effluent brine produced by freeze separation, in order to design a monitoring program for the project. Road salts in the vadose zone will not be affected by extraction of groundwater, and are not included in this method of calculation.

Site parameters that must be known for planning the monitoring program are:

- the average salt contaminant concentration in the contaminated groundwater (C_{gw}),
- the volume of contaminated groundwater (v_{gw}), and total volume of groundwater (v_{tot}) to be extracted for treatment,
- the volume (v_{soil}) and density (ρ_{soil}) of contaminated soil below the groundwater table, so that the mass of soil (m_{soil}) can be calculated from v_{soil} and ρ_{soil},
- the average salt concentration in the soil below the groundwater table (C_{soil}), as tested in drained soil samples. Any salt contaminated groundwater that occupies immobile pore spaces will re-contaminate groundwater flowing in to replace the groundwater extracted for treatment. These salts must be accounted for in the final mass of road salts in the soil and groundwater when remediation is finished.
- the average daily maximum air temperature (T_{air}) during the treatment period (from meteorological records), defined as the design temperature, and
- the allowable salt concentration (C_{allow}) after treatment.

Using these known values, follow this sequence of calculations:

1. From Table 4.5 or Figure 4.4, find the maximum effluent brine concentration produced by freeze separation (C_f) at the design temperature (T_{air}).

2. The total mass of salt dissolved in groundwater at the site (m_{tot}) is calculated as:

   $$m_{tot} = (v_{gw}\, C_{gw}) + (m_{soil}\, C_{soil}) \qquad [4.6]$$

3. The mass of salt that can remain at the site (m_{allow}) is calculated as:

   $$m_{allow} = v_{gw}\, C_{allow} \qquad [4.7]$$

   Note that dissolved salts that will not be removed with groundwater extraction are included in the mass of salt that can remain at the site.

4. The mass of salt that must be removed by treatment (m_{rem}) is calculated as:

   $$m_{rem} = m_{tot} - m_{allow} \qquad [4.8]$$

   Note that at sites where a significant quantity of salt cannot be extracted in the groundwater, m_{allow} will be smaller and m_{rem} will be larger than for sites where most of the salt can be extracted in groundwater.

5. The volume of groundwater that will be removed from the salt as effluent brine (v_{brine}) is calculated as:

   $$v_{brine} = m_{rem} / C_f \qquad [4.9]$$

6. The volume of groundwater that will remain as ice (v_{ice}) is calculated as:

   $$v_{ice} = v_{tot} - v_{brine} \qquad [4.10]$$

7. The maximum allowable concentration of salt in the ice produced by freeze separation (C_{ice}) is calculated as:

   $$C_{ice} = m_{allow} / v_{ice} \qquad [4.11]$$

Electrical conductivity (EC) measurements of the effluent brine can be used as a surrogate field test of contaminant concentration, if a site specific relationship has been developed. During treatment, effluent brine concentration can be monitored continually using an electroconductivity meter and datalogger. For maximum treatment efficiency, goundwater extraction should be suspended when either of the following conditions are observed during treatment:

- Actual air temperature > T_{air}, or
- Measured effluent brine concentration < C_f

When either of these conditions are present, the concentration of effluent brine produced will be less than was anticipated during design. The result will be a greater volume of effluent brine produced, which will raise the unit cost of treatment. To reduce labor costs during treatment, an automated feedback control system could be installed that reduces the pumping rate when these conditions are present.

So long as the effluent brine produced is at the maximum concentration possible for the design temperature (T_{air}), there will not be any benefit to re-cycling the effluent brine for additional freeze separation at that temperature. It may be possible to recycle effluent brine when the actual air temperature is much less than T_{air}, in order to reduce the quantity of effluent brine produced for disposal. With the additional appropriate control system for the pumps and valves, re-cycling the effluent brine for further freeze separation could produce an incremental benefit by reduction of the quantity of effluent brine produced. The designer will have to determine if the additional expenses to recycling the effluent brine can be cost effective.

Depending on site orientation and the time of year, solar radiation may raise the apparent air temperature or reduce the amount of ice produced from the groundwater, decreasing the concentration of effluent brine produced during freeze separation. Installing an automated control for intermittent operation, covering the retaining pond or changing the orientation or placement of the retaining pond can reduce or eliminate this effect.

4.5.5 Effluent brine removal

The rate of production of effluent brine can be adjusted by changing the groundwater extraction pumping rate. The effluent brine must be collected for removal, and the size of the collection tank or sump will depend on the how frequently the effluent brine is to be removed. Due to drainage from the ice mass by gravity or melting, there will still be effluent brine produced after extraction pumping is completed. When the effluent brine concentration is less than the allowable concentration (C_{allow}), the effluent does not need to be removed for disposal.

The equipment used to remove the effluent brine produced by freeze separation and transport it for disposal must be selected to operate under prolonged exposure to the corrosive salt brine.

The remediation designer may be able to find a use for the effluent brine, turning a disposal cost into a revenue source. Two possible uses of the effluent brine are as a feed stock for production of pre-wetting liquids for snow and ice control, or as a dust control agent for gravel road maintenance. If the effluent brine is to be stored for other uses, then the remediation budget may need to include purchase of storage tanks.

4.6 Calculation of significant length for thin film freezing

Groundwater treated by freeze separation forms two products: ice and effluent brine. The final concentration of effluent brine produced by freeze separation is a function of its temperature; normally this will be equal to the air temperature (see Section 4.5.4 for a discussion of maximum effluent brine concentration C_f at air temperature T_{air}). The effluent brine will be removed for off-site disposal, while the treated water from melted ice can either be injected into the ground, allowed to join the surface flow during the spring melt, or be retained for other uses. So long as the concentration of salt in the ice (defined in Section 4.5.4 as C_{ice}) is less than the applicable regulatory limit, there will be no restriction on how the treated water is handled. Note that during the ESAs other contaminants may be identified, which could impose additional restrictions on handling and disposal of the treated groundwater. For the remainder of this section, it is assumed that road salts are the only groundwater contaminant present.

Given that the treated water meets regulatory limits, the final concentration of road salts in the effluent brine produced by freeze separation is only important in that the more concentrated the brine, the smaller the volume for disposal and lower the unit cost of treatment. Theoretically, with properly designed and operated freeze separation, there will not be any requirement to contain the melted ice water after the effluent brine has been removed. In practice, however, it would be prudent to hold the treated water until it can be confirmed that it is at or below the required concentration. This usually means that a retaining pond is required as part of the remediation project. The purpose of the retaining pond is to store the ice mass produced by freeze separation, store effluent brine produced by freeze separation for removal, retain the initial melt water from the ice mass which has the majority of contaminant trapped during freezing (as discussed in Section 4.1), and possibly to store the melted water prior to its disposal.

There are three possible methods of handling the groundwater during freeze separation, each of which requires a different set of criteria for design of a retaining pond.

- Extracted groundwater can be pumped directly into a retaining pond. Ice will form on the surface of the water, with brine underneath. As the ice mass grows thicker during exposure to freezing temperatures, the brine will become more concentrated. The critical design parameter is the thickness of ice produced, as discussed in Section 4.4. The depth of the retaining pond must be chosen so that it is greater than the predicted ice thickness. Once the depth of the pond has been determined, the size and shape of the retaining pond will be determined by site considerations and the total volume of groundwater to be extracted.
- Extracted groundwater can be sprayed into the air to freeze in droplets. The brine produced will form a thin film on the icy nucleus as the droplet freezes in the air. As the icy droplets settle to the ground, they fuse together into an ice mass, and the effluent brine will drain under gravity through the pore spaces between droplets, to be collected at the margins of the ice mass. Gao (1998) and Instanes (1993) discuss the formation of the ice mass from spray freezing. The critical design parameter of the

retaining pond is the area covered by the ice mass, with special consideration for droplet drift due to wind. Depth of the retaining pond will depend on the volume of groundwater to be treated. Horizontal dimensions of the retaining pond will depend on the area needed to capture the spray.

- Extracted groundwater can flow in sheets across an ice surface, successively adding thin layers of ice to the top of the ice mass. The effluent brine produced by freeze separation will drain across the surface to the lowest point for collection. The critical design parameters of the retaining pond will be the width and length; the width will be determined by the extraction pumping rate, and the length will be chosen so that the groundwater has completely separated into ice and effluent brine before it reaches the pond's lowest point. The distance that groundwater will flow before the ice and effluent brine are completely separated is defined, for further discussion, as the significant length.

No reference was found that could be applied to the design of a retaining pond for freeze separation treatment using thin sheet flow over an ice surface. The remainder of this section describes the development of an analytical model for this situation.

The conceptual model for freeze separation by thin sheet flow above an ice surface is shown in Figure 4.6. Groundwater flows from one side of a rectangular retaining pond. The base of the retaining pond is sloped just enough to create a laminar, gravity-induced flow (approximately 0.2 to 0.3%), with a sump to collect effluent brine along the lowest side. Groundwater entering the retaining pond contains specific heat energy from its initial temperature and kinetic energy, and may gain radiant solar energy. As soon as the groundwater enters the pond, it begins to lose heat energy through:

- conduction,
- convection,
- evaporation,
- internal and external friction,
- radiation,
- heat absorbed in melting snow falling onto the flowing liquid, and
- potential energy as it flows from the entry point to the lowest point in the pond.

The following assumptions were made when developing the model for calculating significant length:

- Thin sheets of groundwater move only as laminar flow across the upper surface of the retaining pond.
- The flowing groundwater has uniform temperature at all depths.
- The only significant energy in the groundwater entering the retaining pond is its initial heat energy (i.e., specific heat) and energy released as the latent heat of fusion; the kinetic energy of laminar groundwater flow and incident solar radiation energy in the retaining pond are ignored.
- Energy losses by evaporation, radiation, the melting of falling snow, external and internal friction are not significant, when compared to the energy losses by conduction and convection, and are ignored.
- The calculation of energy losses by convection assumes that the air above the ice is calm and that wind does not contribute to convective heat loss.
- Physical parameters of groundwater will change slightly near the freezing point, but the variation (shown in Table 4.6) are not significant.

- The ground below the retaining pond will be at air temperature before any groundwater is pumped into the retaining pond. The amount of energy added in the groundwater is assumed to be insignificant in relation to the heat storage capacity of the mass of the ground, and the ground temperature is assumed a constant during treatment. In reality, the soil temperature will vary with depth below the pond liner, but this is neglected in the development of the model.

The conceptual model is treated as two separate heat exchange regimes. In the first heat regime, groundwater flows in a thin film with constant velocity, mass and salt concentration from a series of outlets spaced across the upper surface of the retaining pond. Heat energy is lost by groundwater to the upper surface of the pond through conduction, and by convection to the air above. This regime ends when the groundwater temperature reaches its freezing point. The average of the initial groundwater temperature and the air temperature is used to calculate the heat flow rate in this regime. The total amount of energy, and the distance that the groundwater will travel in this regime (l_{sl}), is a function of the groundwater outlet temperature (T_{out}).

The second heat exchange regime begins at the point the groundwater cools to its freezing point and the groundwater begins to separate into ice crystals and brine. Brine concentration increases as ice forms until the effluent brine reaches the maximum concentration possible at the ambient temperature (see Table 4.5). As ice forms, the mass flow rate, thickness and velocity of the flowing fluid decrease while salt concentration increases. The rate of latent heat of fusion released by the formation of ice crystals is equal to the rate of heat lost by conduction and convection, and the mass removed from the flow is calculated as a fraction of the total latent heat available from the formation of ice in the flowing water. To simplify the mass balance calculation, the conceptual model assumes that ice crystals grow on the frozen surface below the brine, so that the flowing fluid contains only brine. Once the flowing brine cools to air temperature and reaches its maximum concentration, it will flow at constant velocity and concentration to the collection sump at the lowest point of the retaining pond. Figure 4.7 shows the two heat exchange regimes, groundwater temperature, and brine concentration along the line of flow. Appendix 1 describes a calculation method developed for predicting significant length for a given mass flow rate, air temperature and initial groundwater concentration. The total amount of energy, and the length required for the second regime (l_{sII}), is a function of the air temperature, fluid freezing temperature and initial salt concentration. The significant length is the sum of the lengths required by the two heat regimes. Figure 4.8 is taken from the significant lengths calculated over a range of air temperatures, mass flow rates per unit width, and initial concentration. Inspection of the detailed figures in Appendix 6, which are taken from the calculated distances in Table 4.7, shows that the initial concentration of dissolved salts is less important than the mass flow rate and air temperature. Figure 4.8 uses the calculations for an initial concentration of 10,000 mg/L to get an initial value of significant length to use in design of a retaining pond, as described below.

The intention for retaining pond design is to minimize the length of the pond such that the maximum effluent brine concentration is reached in the flowing liquid immediately before the brine drains into the sump for disposal. Making the retaining pond longer than the significant length adds to the cost without any increase in the efficiency of the separation process. As such, retaining pond design is heavily dependent on air temperature and flow rate. Note, however, that convective cooling due to air movement (i.e., wind) will reduce the significant length; this has been ignored in this analysis.

The conceptual model for the retaining pond assumes a rectangular shape. Site considerations will influence the shape and size of the pond. The process proposed for retaining pond design is:

1. From local meteorological records, determine the average maximum daily air temperature as the design temperature. By using the average daily high temperature, the majority of freeze separation will occur at or below the design temperature.
2. From the ESA, determine the average concentration of road salts in the groundwater (C_{gw}) to be extracted for treatment.
3. From site considerations, choose an initial width for the retaining pond.
4. Using the design groundwater extraction pumping rate (discussed in Section 4.2) and the initial pond width, determine the initial mass flow rate per unit width of the retaining pond.
5. From Figure 4.8, using the initial mass flow rate per unit width and the design temperature, determine the preliminary significant length. Note that the concentration of the groundwater at the outlet is not a factor in determining the preliminary significant length.

6. Evaluate whether the initial width and preliminary significant length are suitable for the site. If necessary, change the initial width and then determine a new preliminary significant length.
7. Once the final design width of the pond has been selected, recalculate the mass flow rate per unit width.
8. Using Table 4.7, determine the final design significant length for the initial groundwater salt concentration (C_{gw}), design temperature (T_{air}) and mass flow rate per unit width ($\dot{M}$). Note that the lengths in Table 4.7 are rounded off to tenths of a meter; there is no practical need for any greater accuracy in pond design.
9. Knowing the length and width of the retaining pond, calculate the depth needed to contain the total volume of groundwater that is planned to be extracted.

In practice, the maximum daily temperature will fluctuate from day to day. When the actual air temperature is higher than the design temperature, freeze separation treatment will not produce effluent brine to the design target concentration (defined in Section 4.5.4 as C_f) and the actual significant length will be longer than the significant length at the design air temperature. More importantly, groundwater will still be warmer than its freezing point temperture when it reaches the distance calculated for the first heat transfer regime. The groundwater can then melt through ice previously formed, and the flow will be beneath the ice instead of above it. The groundwater cannot resume flow across the surface of the ice sheet until the actual air temperature falls to below the design temperature and ice plugs the melted channels along the bottom of the retaining pond. For this reason, it is suggested that the project use automated temperature sensor control to stop pumping when actual air temperature is warmer than the design temperature or concentration of effluent brine produced is less than C_f.

Table 4.1 Drinking water standards for road salt constituents

Substance	Guideline type	Concentration (mg/L)
Sodium	Aesthetic objective	≤ 200
Chloride	Aesthetic objective	≤ 250
Calcium	No guidelines	n/a
Magnesium	No guidelines	n/a

(from Health Canada, 1999)

Table 4.2 Surface water quality guidelines for road salt constituents

Substance	Guideline	Maximum Concentration (mg/L)	Continuous Concentration (mg/L)
Sodium	No guideline	n/a	n/a
Chloride	Guidelines for the protection of freshwater aquatic life (from USEPA guidelines)	860	230
	Guidelines for Agricultural Use (irrigation water)	100 to 700 (varies by crop species)	n/a
Calcium	Guidelines for Agricultural Use (livestock water)	1,000	n/a
Magnesium	No guideline	n/a	n/a

(from Alberta Environment, 1999)

Table 4.3 Wetland establishment on reclaimed oil sands lease guidelines for road salt constituents

Total Dissolved Solids (TDS) (mg/L)	Electro-conductivity (mS/cm)	Water Quality (mg/L TDS)	Soil Salinity (mS/cm)
34 to 1,700	0.04 to 2	Suitable for drinking: 500 Suitable for livestock: 5,000 Suitable for recreation: no limit	Non-saline: < 2

(from Oil Sands Wetlands Working Group, 2000)

Table 4.4 Typical porosity's for various aquifer soil types

Material	Porosity of loose material (%)	Porosity of dense material (%)
Uniform clean sand	50	29
Uniform inorganic silt	52	29
Well-graded silty sand	47	23
Well –graded clean sand (fine to coarse)	49	17
Well-graded micaceous sand	55	29
Well-graded silty sand and gravel	46	12

(from Holtz and Kovaks, 1981)

Table 4.5 Maximum concentration for the sodium chloride / water solution at various air temperatures

Air Temp (K)	NaCl - Ice phase (mg/L)	NaCl - Hydrolite phase (mg/L)
273	0	
272	15,900	353,400
271	33,500	351,800
270	51,500	350,500
269	67,400	347,300
268	84,200	345,600
267	101,300	343,600
266	116,800	339,900
265	130,700	337,100
264	147,100	335,000
263	159,700	330,900
262	175,700	328,900
261	190,400	327,300
260	207,100	324,800
259	220,200	322,800
258	232,900	320,700
257	245,100	317,500
256	253,300	314,600
255	265,600	311,700
254	277,000	307,200
253	287,200	304,400
252	298,700	300,700

(from Grant, 2000)

Table 4.6 Physical parameters for water near freezing

Groundwater temperature (K)	Kinematic Viscosity (m^2/s)	Specific Heat (J/[kg K])	Density (kg/m^3)	Enthalpy (J/kg)
273	1.79 e-6	4,218	999.870	102.6
274	1.73 e-6	4,214	999.903	4,318.4
275	1.67 e-6	4,211	999.935	8,530.8
276	1.62 e-6	4,208	999.968	12,740.0
277	1.57 e-6	4,205	1000.000	16,946.2
278	1.52 e-6	4,202	999.990	21,149.8
279	1.47 e-6	4,200	999.938	25,325.0
280	1.43 e-6	4,198	999.886	29,526.0
281	1.39 e-6	4,196	999.834	33,725.0
282	1.35 e-6	4,194	999.782	37,941.0
283	1.31 e-6	4,192	999.730	42,134.1

(from Weast, 1973)

Table 4.7 Significant Length for design of retaining ponds used in freeze separation by thin film flow over an ice surface (for a groundwater inlet temperature = 275 K)

Air Temp (K)	Mass Flow (kg/s m)	l_s for C_{gw} = 500 mg/L (m)	l_s for C_{gw} = 5,000 mg/L (m)	l_s for C_{gw} = 10,000 mg/L (m)	l_s for C_{gw} = 20,000 mg/L (m)	l_s for C_{gw} = 30,000 mg/L (m)	l_s for C_{gw} = 40,000 mg/L (m)	l_s for C_{gw} = 50,000 mg/L (m)	l_s for C_{gw} = 60,000 mg/L (m)	l_s for C_{gw} = 80,000 mg/L (m)	l_s for C_{gw} = 100,000 mg/L (m)
271	0.10	2.8	3.3	3.4	3.1	2.3					
271	0.25	9.6	11.3	11.8	10.6	7.7					
271	0.50	24.0	28.2	29.5	26.6	19.1					
271	0.75	41.0	48.3	50.5	45.5	32.7					
271	1.00	60.0	70.7	73.9	66.5	47.8					
271	2.00	150.2	177.0	185.0	166.5	119.6					
271	4.00	375.3	442.1	462.0	415.4	298.7					
269	0.10	1.4	1.7	1.8	1.9	2.1	2.0	1.7	1.5		
269	0.25	5.0	5.8	6.2	6.6	7.2	6.9	5.9	5.1		
269	0.50	12.6	14.7	15.8	16.9	18.3	17.4	15.1	12.9		
269	0.75	21.6	25.2	27.2	28.9	31.4	29.9	25.9	22.2		
269	1.00	31.6	36.8	39.7	42.3	45.8	43.6	37.8	32.4		
269	2.00	79.0	92.2	99.4	105.9	114.7	109.3	94.6	81.1		
269	4.00	197.1	229.9	248.0	264.1	286.3	272.6	236.0	202.3		
267	0.10	0.9	1.1	1.2	1.3	1.4	1.4	1.4	1.5	1.4	0.3
267	0.25	3.4	3.9	4.2	4.5	4.9	5.0	5.0	5.2	4.9	1.0
267	0.50	8.6	9.9	10.7	11.6	12.6	12.8	12.7	13.2	12.5	2.2
267	0.75	14.7	16.9	18.2	19.8	21.6	21.9	21.7	22.5	21.3	4.2
267	1.00	21.5	24.8	26.8	29.1	31.7	32.2	31.8	33.0	31.2	6.2
267	2.00	53.7	61.9	66.9	72.7	79.2	80.4	79.5	82.5	78.0	12.9
267	4.00	133.9	154.4	166.9	181.4	197.6	200.4	198.2	205.8	194.8	32.3
265	0.10	0.6	0.8	0.8	0.9	1.0	1.0	1.0	1.1	1.1	0.9
265	0.25	2.5	2.9	3.1	3.4	3.7	3.8	3.8	4.0	4.0	3.4
265	0.50	6.5	7.4	8.0	8.7	9.5	9.7	9.8	10.2	10.2	8.8
265	0.75	11.2	12.7	13.7	15.0	16.2	16.6	16.8	17.4	17.5	15.0
265	1.00	16.3	18.6	20.1	21.9	23.7	24.3	24.6	25.5	25.5	21.9
265	2.00	40.8	46.6	50.3	54.9	59.4	61.0	61.5	63.8	64.0	54.9
265	4.00	101.6	116.2	125.5	136.8	148.2	152.1	153.3	159.2	159.5	137.0
263	0.10	0.5	0.5	0.6	0.7	0.7	0.8	0.8	0.8	0.9	0.8
263	0.25	2.0	2.3	2.5	2.7	2.9	3.0	3.1	3.2	3.3	3.1
263	0.50	5.2	5.9	6.3	6.9	7.5	7.7	7.8	8.2	8.3	7.8
263	0.75	9.0	10.2	11.0	12.0	12.9	13.4	13.6	14.1	14.4	13.6
263	1.00	13.1	14.9	16.1	17.5	18.9	19.5	19.9	20.7	21.1	19.9
263	2.00	32.9	37.4	40.3	44.0	47.5	49.0	49.9	51.8	52.9	49.8
263	4.00	81.8	93.0	100.2	109.5	118.2	122.0	124.1	128.8	131.7	124.0
261	0.10	0.5	0.5	0.5	0.5	0.6	0.6	0.5	0.7	0.7	0.7
261	0.25	1.7	1.9	2.0	2.2	2.4	2.5	2.5	2.6	2.7	2.7
261	0.50	4.3	4.9	5.2	5.7	6.2	6.4	6.6	6.8	7.1	6.9
261	0.75	7.5	8.5	9.1	10.0	10.7	11.1	11.4	11.8	12.3	12.0
261	1.00	11.0	12.4	13.4	14.6	15.7	16.3	16.7	17.3	17.9	17.6
261	2.00	27.5	31.1	33.4	36.5	39.3	41.1	41.7	43.4	44.9	43.9
261	4.00	68.4	77.4	83.3	91.0	98.0	101.6	104.0	108.1	111.8	109.4
259	0.10	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5
259	0.25	1.4	1.6	1.7	1.9	2.0	2.1	2.1	2.2	2.3	2.3
259	0.50	3.7	4.2	4.5	4.9	5.2	5.5	5.6	5.8	6.1	6.0
259	0.75	6.5	7.3	7.8	8.5	9.2	9.5	9.8	10.2	10.6	10.5
259	1.00	9.5	10.6	11.4	12.5	13.4	13.9	14.3	14.9	15.5	15.4
259	2.00	23.7	26.6	28.6	31.2	33.6	34.9	35.8	37.2	38.7	38.6
259	4.00	58.8	66.2	71.2	77.7	83.6	86.8	89.2	92.6	96.4	96.0

Table 4.7 Significant Length for design of retaining ponds used in freeze separation by thin film flow over an ice surface (continued) (for a groundwater inlet temperature = 275 K)

Air Temp (K)	Mass Flow (kg/s m)	l_s for C_{gw} = 500 mg/L (m)	l_s for C_{gw} = 5,000 mg/L (m)	l_s for C_{gw} = 10,000 mg/L (m)	l_s for C_{gw} = 20,000 mg/L (m)	l_s for C_{gw} = 30,000 mg/L (m)	l_s for C_{gw} = 40,000 mg/L (m)	l_s for C_{gw} = 50,000 mg/L (m)	l_s for C_{gw} = 60,000 mg/L (m)	l_s for C_{gw} = 80,000 mg/L (m)	l_s for C_{gw} = 100,000 mg/L (m)
257	0.10	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4
257	0.25	1.2	1.4	1.5	1.6	1.7	1.8	1.8	1.9	2.0	2.0
257	0.50	3.2	3.6	3.9	4.2	4.5	4.7	4.9	5.1	5.3	5.3
257	0.75	5.6	6.3	6.7	7.3	7.9	8.2	8.4	8.7	9.1	9.1
257	1.00	8.3	9.3	10.0	10.9	11.7	12.1	12.5	13.0	13.5	13.5
257	2.00	20.8	23.3	25.0	27.3	29.3	30.4	31.3	32.4	33.8	33.9
257	4.00	51.6	58.0	62.2	62.2	72.9	75.7	77.9	80.8	84.1	84.3
255	0.10	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
255	0.25	1.0	1.2	1.3	1.4	1.5	1.6	1.6	1.7	1.8	1.8
255	0.50	2.9	3.2	3.4	3.7	4.0	4.2	4.3	4.5	4.6	4.7
255	0.75	5.0	5.6	6.0	6.5	7.0	7.2	7.5	7.7	8.0	8.1
255	1.00	7.4	8.3	8.9	9.7	10.3	10.8	11.1	11.5	11.9	12.0
255	2.00	18.4	20.7	22.1	24.1	25.8	26.9	27.6	28.6	29.8	29.9
255	4.00	45.9	51.5	55.2	60.2	64.5	67.0	68.9	71.4	74.3	74.7
253	0.10	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
253	0.25	1.0	1.0	1.1	1.2	1.3	1.4	1.4	1.5	1.5	1.6
253	0.50	2.6	2.9	3.1	3.3	3.6	3.7	3.8	4.0	4.1	4.2
253	0.75	4.5	5.0	5.3	5.8	6.2	6.5	6.7	6.9	7.2	7.3
253	1.00	6.7	7.5	8.0	8.7	9.3	9.6	9.9	10.3	10.7	10.8
253	2.00	16.6	18.6	19.9	21.7	23.2	24.1	24.8	25.7	26.7	26.9
253	4.00	41.4	46.4	49.7	54.1	57.9	60.2	61.9	64.1	66.7	67.2

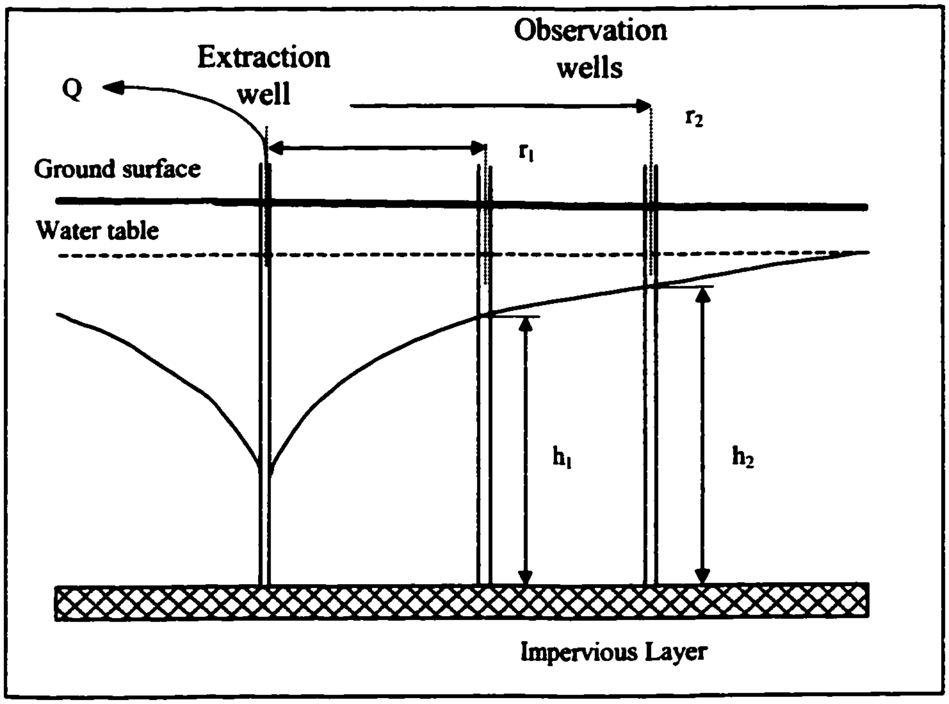


Figure 4.1Pumping rate / hydraulic conductivity model variables used in equation [4.2]

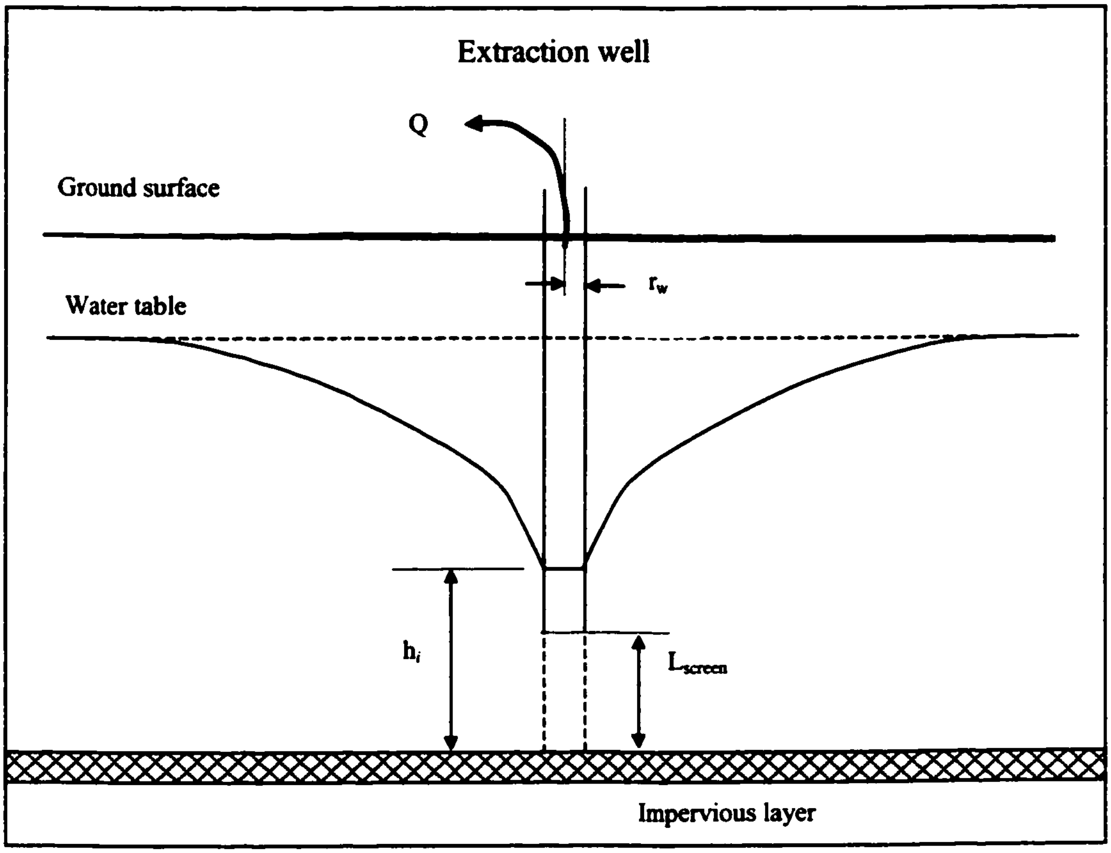


Figure 4.2 Single well test for calculating hydraulic conductivity

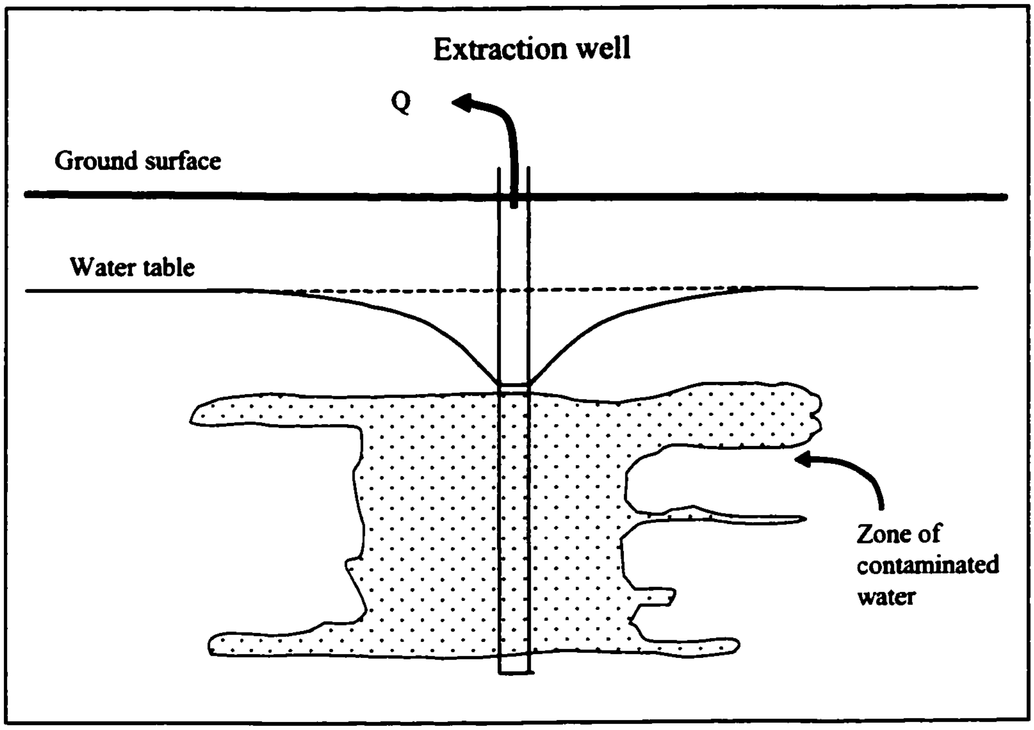


Figure 4.3 Conceptual model for contaminant removal by groundwater extraction

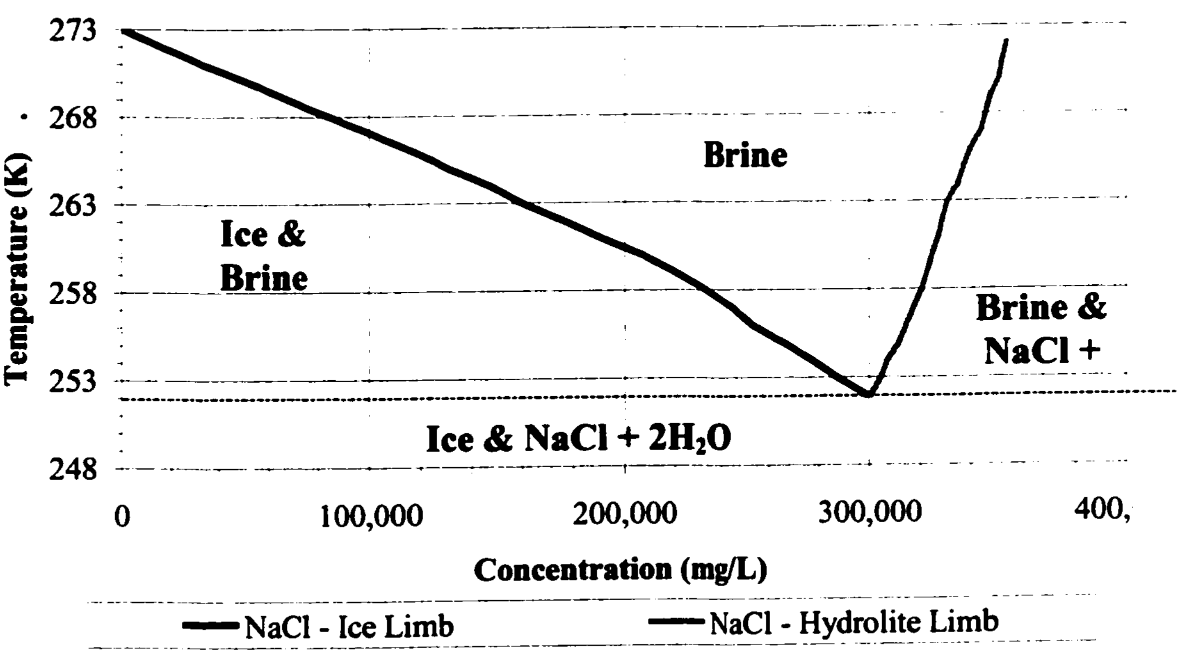


Figure 4.4 Phase diagram for NaCl – ice system
(after Grant, 2000)

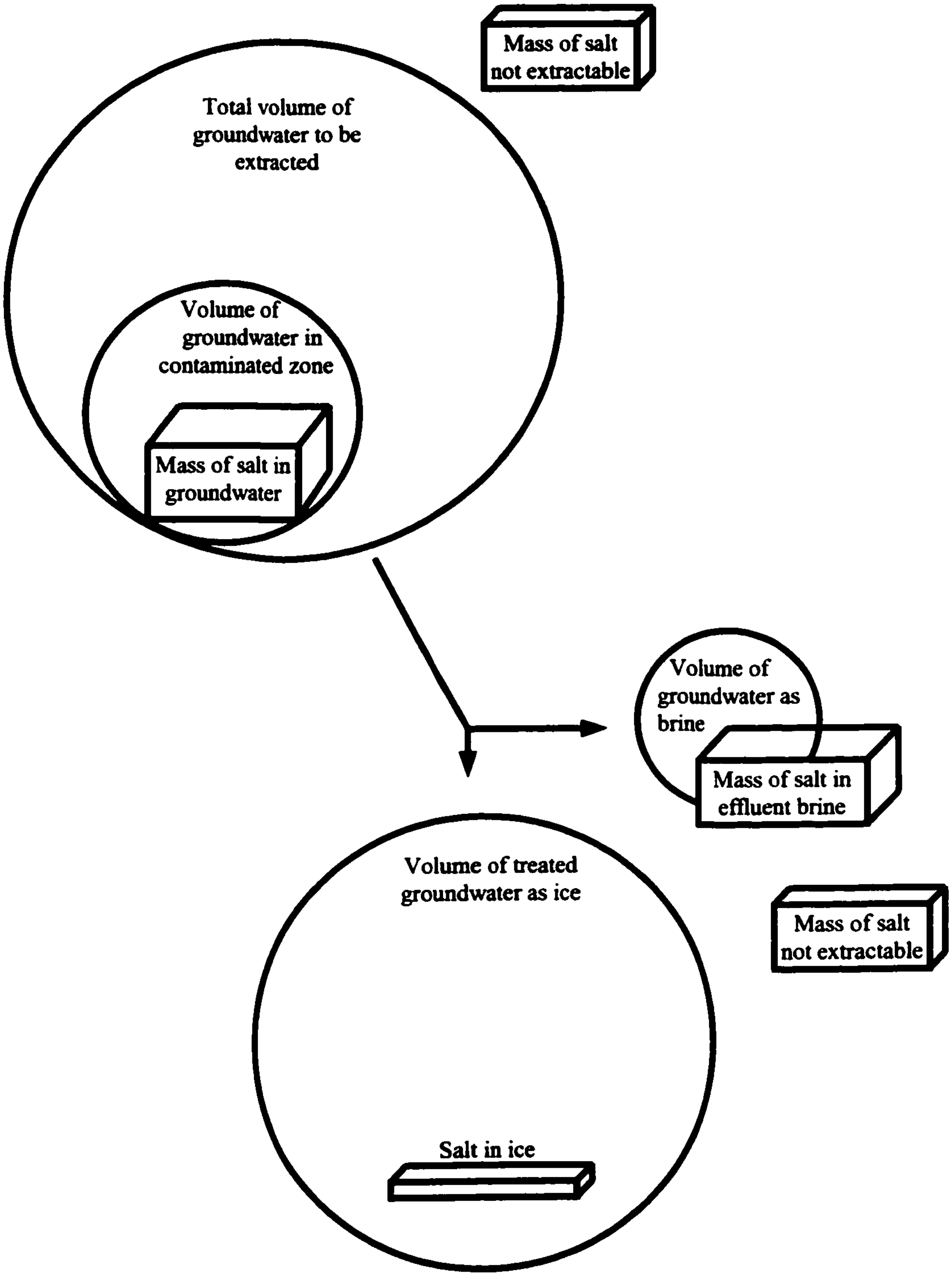


Figure 4.5 Conceptual model of the masses of groundwater and dissolved road salts in freeze separation treatment

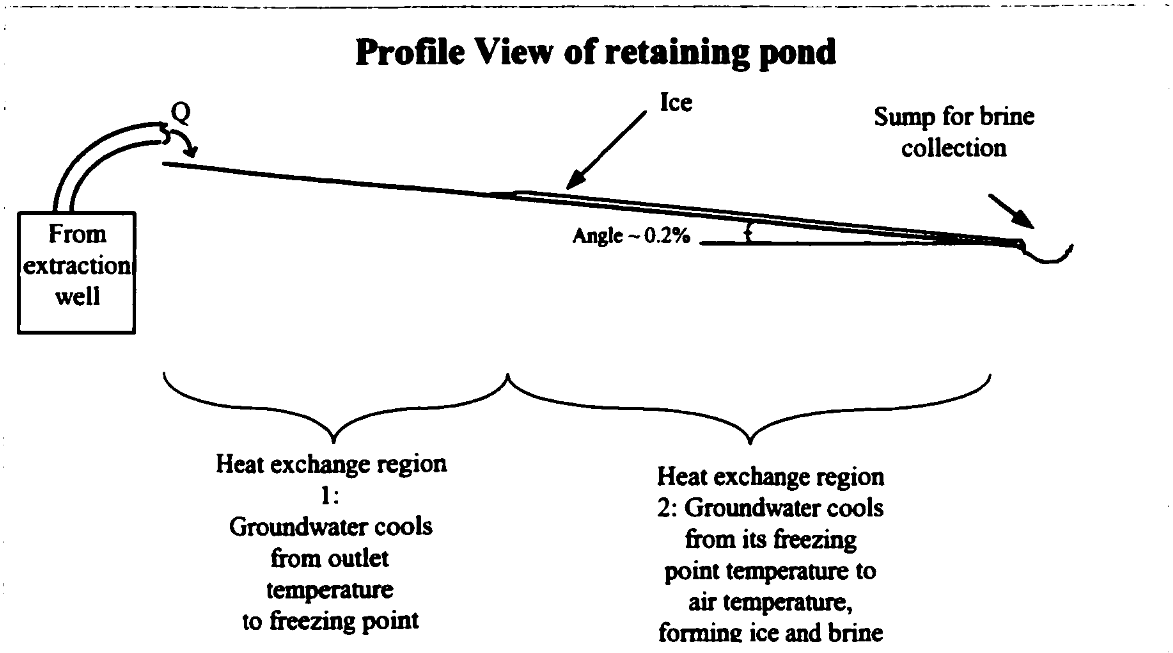


Figure 4.6 Conceptual model for freeze separation by thin sheet flow above an ice surface

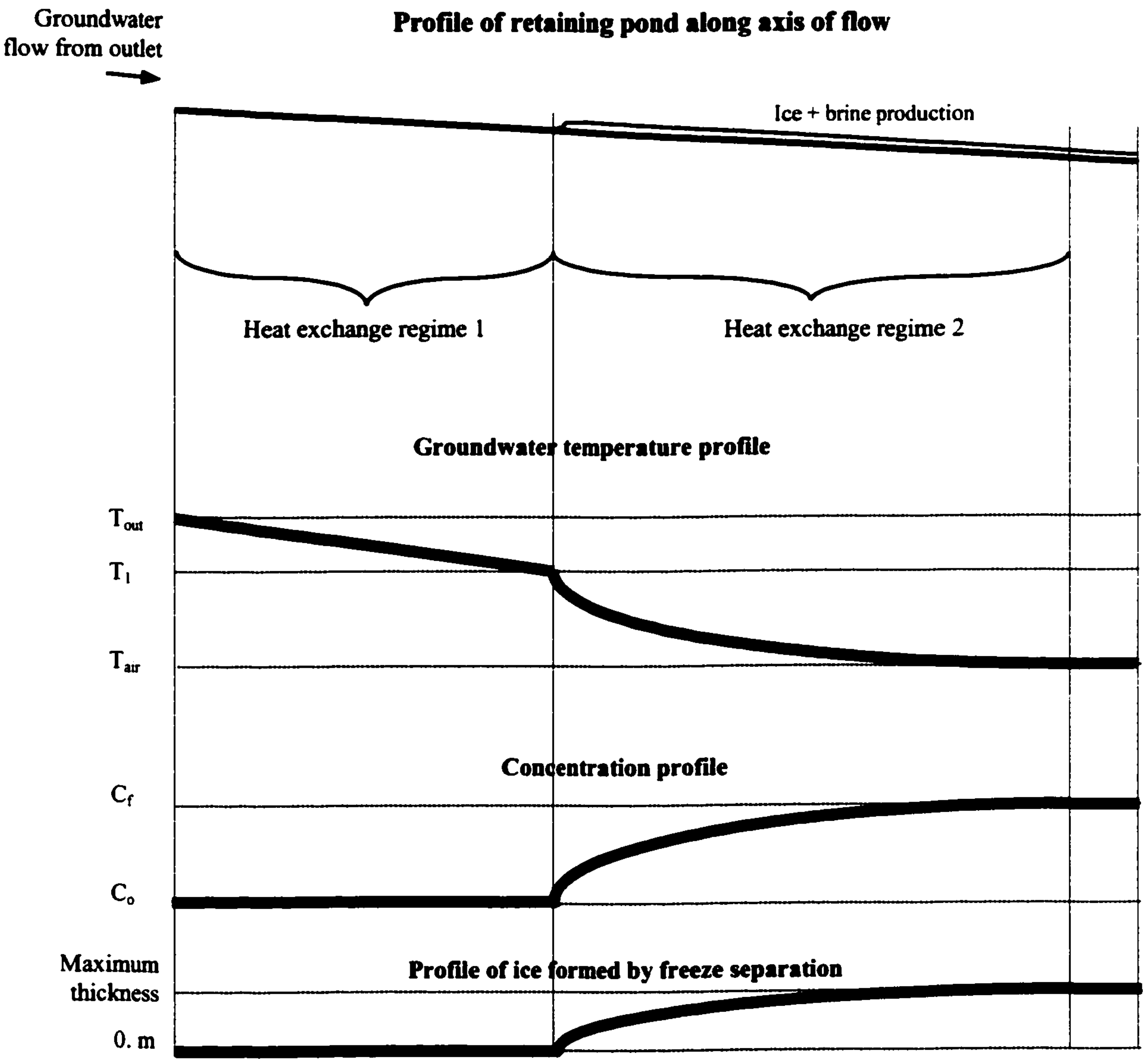


Figure 4.7 Heat exchange regimes, groundwater temperature, concentration profiles and thickness of ice formed by freeze separation along the axis of flow

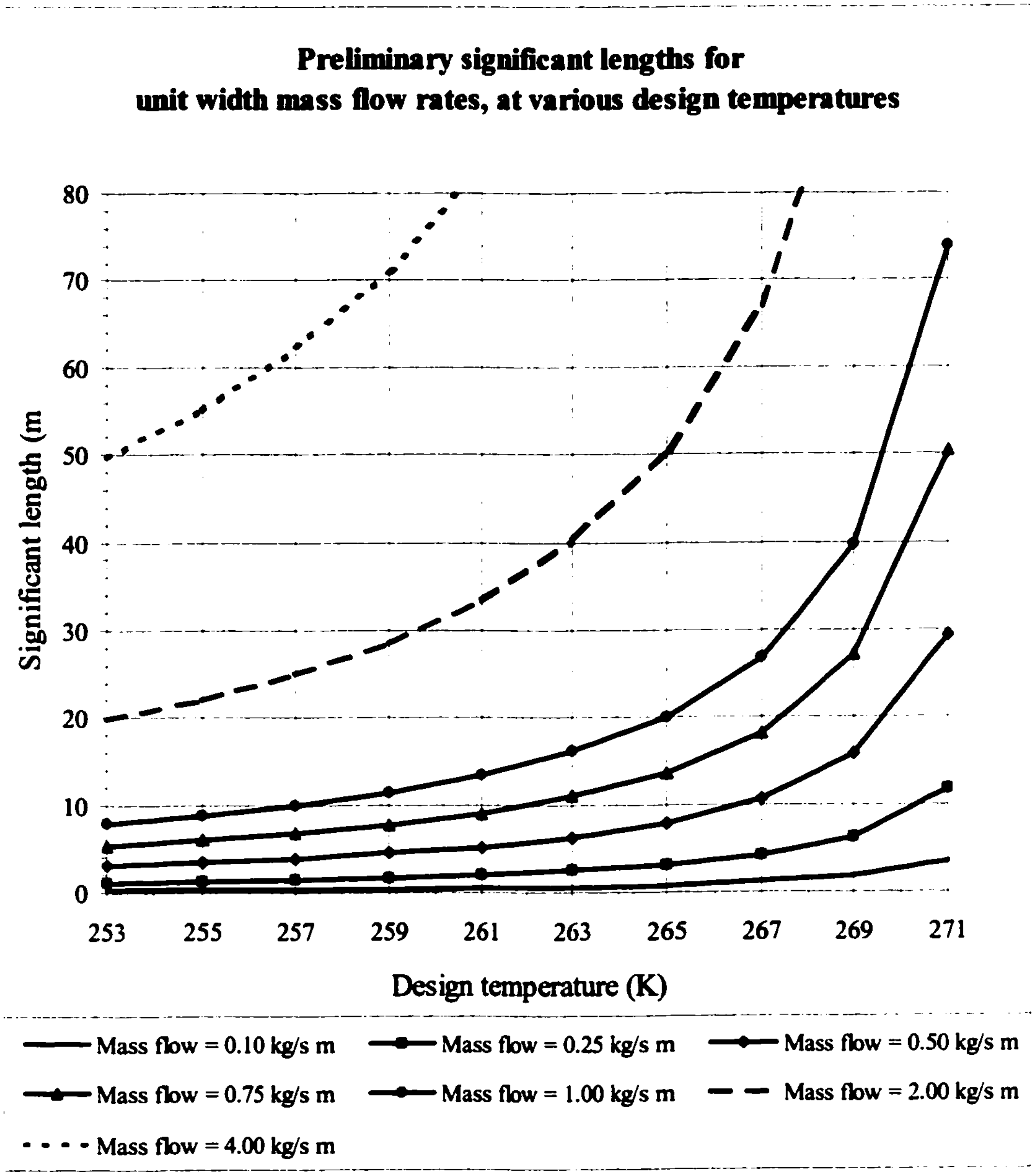


Figure 4.8 Preliminary significant length for various design temperatures and mass flow rates per unit width

Chapter 5

DEMONSTRATION PROEJCT; OBED MAINTENANCE SITE, FEBRUARY 2001

5.1 Introduction

The objective of the demonstration project was to confirm the theoretical potential for freeze separation as a cost effective technique for ex-situ treatment of contaminated groundwater, and to gain practical experience for the development of guidelines for planning remediation projects using freeze separation treatment.

5.2 Site description

5.2.1 Location

The demonstration project was conducted at the Obed Maintenance site, located on the north-east quarter of Section 3, Township 53, Range 22 west of the 5th Meridian, just north of Highway 16 between Edson and Hinton in west-central Alberta, Canada (as shown in Figure 5.1). The site is an obtuse triangle, 1.44 hectares of publicly owned land southwest of Obed Lake. The general area is higher to the south and southwest, gently sloping to the north towards the Athabasca River with an elevation at the demonstration site of about 1,070 m. The surrounding area is covered with spruce - poplar forest and spruce swamp. A public campsite on the shores of Obed Lake, about 500 m to the northeast, is the only development in the area. Railroad tracks run parallel to the highway on the south side of the road, uphill from the site.

The Obed site has a cleared area along its southern edge, bordered by natural forest on the remainder of the property. The treed portion slopes gently to the north, with a short steep downward transition down at the edge of the cleared area. Chinooks (westerly winds) and upslope precipitation (easterly winds) from the front ranges of the Rocky Mountains affect the area, and the site has greater annual snowfall and warmer average temperatures than in the Town of Edson, 50 km to the east.

5.2.2 Geology

The open areas in the Obed Maintenance site have been leveled with fill above native soil. The site has a 500 mm of sand and gravel fill cover, constructed when the site was developed in 1985. Although no records exist, it is reasonable to assume that the site was leveled using native material before being covered with the sand and gravel fill. Below the sand and gravel fill is a non-homogenous sandy or clayey till, ranging from 2 to 4 m thick above broken soft sandstone or siltstone bedrock. The sandy and clayey tills are characterized by isolated gravel, cobbles, coal fragments and sandy lenses increasing with depth.

5.2.3 Hydrology

A hand-made borehole was dug on September 2000 into undisturbed soil near the northwest boundary of the site. The borehole showed a high infiltration rate, with soil sloughing into the hole starting at 0.3 m below ground level.

Seasonal variation Groundwater elevation measurements in selected observation wells were used to calculate the hydraulic gradient at the site. Table 5.1 shows the calculated hydraulic gradient during the field investigation and demonstration project period. Based on these measurements, the magnitude of the hydraulic gradient is assumed to be constant during the year with seasonal shifts in the direction of gradient. The water table dropped approximately one meter from the fall to mid-winter, as shown in Table 5.2. The change in groundwater level is assumed to be the result of a seasonal decrease from reduced infiltration during the winter.

5.2.4 History

The Obed site was first developed in 1958 as a privately owned store, restaurant, gas station and motel complex to service the newly paved Highway 16 (Green Plan, 1996). Fuel spilled from the gasoline storage tanks has contaminated part of the site, and is now the only evidence left of this private facility. Immediately east of the motel complex was a public campground.

In 1984, the provincial government purchased the motel complex during right–of–way expansion when Highway 16 was twinned. The Obed Maintenance site was developed concurrently with adjacent highway construction, and completed in 1988. The site was used as a "satellite stockpile" site by Alberta Transportation from 1988 to 1995. A satellite stockpile is a facility used to stockpile winter highway maintenance materials with very little other development. In this case, the only development at the Obed maintenance site was a sand stockpile and a wood frame building that housed a front end loader. The sand stockpile at Obed was left uncovered and rested on a gravel pad. The only surface drainage control was a closed-ended trench filled with cobbles and boulders. Any sand that was not used during the winter was left in place over the following spring, summer and fall. New sand was brought, already mixed with de-icing chemicals, from either the Edson or Hinton maintenance yards in the fall of each year.

In 1995, the Obed site was deactivated and the sand stockpile removed. There is no record of any other site remediation at that time. In December 2000, the building was removed and the area surrounding and including the Obed Maintenance site was designated as Obed Provincial Park. In time, the reservation held by Alberta Transportation for use of this public land as a material stockpile site will be revoked and the Obed Maintenance site will be incorporated into the provincial park (Tinge, 2001).

5.2.5 Risk analysis and site selection

The probable source for salt contamination at the Obed site is from the freeze-proofed sand stockpile that was present from 1988 to 1995. In those years, there would have been a persistent leaching of road salts from the stockpile into the gravel and soil layers underneath. Phase I, II and III ESAs conducted at the site between 1995 and 1999 identified a salt contaminated plume extending down to bedrock, underneath the sand stockpile site and down-gradient approximately 18 metres (Green Plan 1996, 1999 and 2000).

In time, the salt plume may reach Obed Lake, a well-known recreational water body. While some degree of dispersion can be expected as the plume travels the 500 m to the lake, flow paths that follow fissures or sandy layers may still have chloride concentrations well above the allowable limits for recreational waters. The only water well that may be affected by the salt contamination is at the Obed Lake campground, approximately 40 m up-gradient from the lake itself.

The present average concentration of the chlorides in the groundwater is ~3,000 mg/L (i.e., about twelve times the drinking water standard of ≤250 mg/L), and the maximum concentration is 6,100 mg/L (Green Plan 2000). There is no anthropogenic demand for the groundwater, and Obed Lake is not expected to be affected for many years. Taking these factors into account, the Property Management section of Alberta Infrastructure has designated this site to be "low risk". As such, plans for remedial work in summer 2001 were postponed indefinitely, and the site has been made available until at least 2002 for geo-environmental research (Snider, 2000).

5.3 Previous site investigations for salt contamination

Between 1995 and 1999, Green Plan Ltd. (Environmental Consultants) conducted Phase I, II and III ESAs at the Obed Maintenance site. A series of boreholes and monitoring wells were installed, and soil vapor, soil and groundwater samples taken and analyzed (Green Plan 1996, 1999 and 2000). Table 5.3 gives the chemical composition of selected groundwater samples taken in November, 1999 as part of the ESA Phase III. Background levels of conductance in groundwater samples were measured at 2.0 mS/cm, while below the sand stockpile location levels in well 99-9 were as high as 16.7 mS/cm.

Electromagnetic surveys in 1998 and 1999 confirmed that the salt contamination was concentrated below the stockpile location, as shown in Figure 5.2 (Green Plan, 1999 and 2000). Salts from the sand stockpile leached through the gravel pad year-round from melt water and precipitation, resulting in a salt plume directly underneath the stockpile location. There is no evidence of wind-transported salt contamination.

Laboratory analysis of samples taken during the Phase II and III ESAs, shown in Table 5.3, show a trend that agrees with the electromagnetic survey results. Of the three wells selected for Table 5.3, 99-10A is the farthest down-gradient from the centre of the contaminated zone. Well 99-9A is slightly east, perpendicular to the groundwater flow gradient and closest well sampled to the centre of contamination. Well 98-1 is on the western edge of the heavily contaminated zone. In a homogenous soil, it would be expected that concentrations would be highest in well 99-9A, lowest in 99-10A, and somewhere in the middle in well 98-1. Review of Table 5.3 shows this pattern for all contaminants except calcium. Possible explanations for calcium being the exception to the trend could be that calcium has preferentially replaced naturally occurring sodium ions in the boundary layers of the clay particles (Mitchell, 1993), or that naturally occurring soil minerals containing calcium are not homogeneously distributed in the soil at the site. High groundwater concentrations of sodium ions are an indication that sodium chloride was used to freeze-proof sand stockpile at the Obed site at some time, although

Alberta Transportation records show that only calcium chloride was used to freeze proof sand transported to this site.

5.4 Demonstration project site investigation in 2000

A review of the ESA reports from the Obed Maintenance site (Green Plan 1999, 2000), indicated that several site parameters needed for design of a freeze separation were not available: specifically hydraulic conductivity and confirmation of the full extent of the contaminated plume. A 1.5 m borehole, dug outside the contaminated zone in the northwest corner of the site, confirmed the soil stratigraphy previously observed (Green Plan Limited 1999 and 2000).

5.4.1 Expanded electromagnetic survey

The original electromagnetic (EM) survey conducted by Green Plan ended at the edges of the open area, and the results of the ESA did not locate the actual extent of the plume. The original grid used by Green Plan in 1999 (Green Plan, 2000) was used as the basis to extend the EM survey into the treed area. A EM – 31 meter was used to manually record conductivity measurements; the contours interpreted from these measurements are shown in Figure 5.3. The EM survey of August, 2000 confirmed the results of the EM survey done during the Phase III ESA, that the contaminant plume was underneath and down-gradient from the former sand storage site.

5.4.2 Background sampling

Groundwater samples were taken from several observation wells at the site, primarily to develop the site specific EC relationship. Groundwater samples were also taken from the hand-dug borehole. No other tests were done with the groundwater samples that were collected.

5.4.3 Well testing

During the site investigation in August 2000, single well drawdown tests were conducted on three observation wells to determine hydraulic conductivity: wells 98-2, 99-9A and 99-10A. Pressure transducers at the bottom of the well measured the change in water level over time using a datalogger. In the test, ten litres of groundwater were removed using a hand pump, and pressure change under natural recharge was recorded. Figure 5.4 shows a typical depth - time chart developed from these tests. Note that there is a large amount of scatter in the recorded data, attributed to noise in the electrical signals from the transducer.

Because of the scatter in the data, a manual process was used to select representative data for calculating hydraulic conductivity. The manual process deleted points that did not fit a visual curve-smoothing pattern, illustrated in Figure 5.5. The magnitude of error introduced by this method was also investigated (see below) and found to be insignificant. The process used to manually select data points from the results of the drawdown test was:

1. Using a chart of all data points collected, a small number of points were visually selected to represent the overall shape of all charted points. Extreme points were not included in the manual selection.
2. Once a sufficient number of representative points were chosen the remainder of the data points were deleted. Since the data points were selected manually, this procedure could have introduced a bias into the calculations of hydraulic conductivity.

To determine the maximum error that could have resulted from manual selection of data points, the hydraulic conductivity of a well was calculated using two manually selected sub-sets of one complete data set. One sub-set was chosen by visually selecting the maximum values from the complete data set, and the second sub-set was chosen from the minimum values. Figure 5.6 shows the difference between the two extremes of data selected in this fashion for well 99-9A. The hydraulic conductivity calculated using these two series of data were 2.2×10^{-4} cm/s (low range) and 4.2×10^{-4} cm/s (high range). The difference in hydraulic conductivity is considerably less than would be expected from small – scale non-homogenous soil conditions, and is assumed insignificant in further analysis.

The Starpoint Software Super Slug© program was used to calculate hydraulic conductivity using the modified Hvorslev graphical method (Starpoint Software, 1995). A demonstration version of this software is distributed by International Ground Water Modeling Center, Colorado School of Mines. Table 5.4 shows the hydraulic conductivity calculated from three well tests. The hydraulic conductivity for the three wells was within one order of magnitude, which is reasonable.

5.5 Design of demonstration project

The demonstration project conducted at the Obed Maintenance site in February 2001 was intended to validate the theoretical application of freeze separation for treatment of salt contaminated groundwater, and give practical experience in operation of a freeze separation treatment to assist the planning of future projects at the lowest possible cost. While it would have been possible to validate the effectiveness of freeze separation for treatment of salt contaminated groundwater with a small volume of groundwater, it was decided to conduct a multi-day demonstration in order to gain practical experience for future remediation projects using freeze separation. The demonstration project was conducted between 12 and 16 February, 2001. Because the demonstration project would be conducted regardless of the actual weather conditions, it was decided that the effectiveness of freeze separation during the demonstration would be assessed only on the final concentration, and no design temperature was used during the design of this project.

As part of the purpose of the demonstration project, some planning decisions were deliberately made to provide the least expensive of several possible methods to perform certain tasks. Decisions that resulted in lower efficiency or poorer experimental technique will be discussed in Section 5.7, Results of the demonstration project.

Observation wells installed during the Environmental Site Investigations in 1998 and 1999 were used to extract groundwater into temporary retaining ponds. To evaluate the effect of input concentration on the freeze separation process, groundwater was extracted from two different wells: 98-1 and 99-9A. Figure 5.7 is a plan view of the test site showing the location of the temporary retaining pond, extraction wells and the heated trailer used to keep the pumps from freezing.

5.5.1 Pumps and plumbing

Pumps Peristaltic pumps were chosen for the demonstration project to provide consistent flow rates. The maximum flow delivered by these peristaltic pumps was less than the output of most commercially available submersible pumps. The peristaltic pumps were installed in a heated trailer midway between the extraction well and the retaining ponds.

An alternative system would have been to use a submersible impeller pump. There is a commercially available submersible pump that fits inside a 50 mm diameter well, which would eliminate the need for a heated enclosure to prevent the pumps from freezing. One of these pumps was ordered, but not delivered in time for use in the demonstration project. It was planned to control the flow rate from this single speed pump by installing a valve at ground level to return a portion of the flow to the well, so that the desired pumping rate out of the well could be maintained.

Plumbing Flexible polyvinyl chloride (PVC) tubing (10 mm inner diameter) was used to bring the groundwater to the retaining ponds. To prevent the lines from freezing, the tubing was laid inside commercially available closed cell foam pipe insulation with an electric heating cable.

5.5.2 Retaining pond and liner

Three small temporary retaining ponds were constructed using above-ground sand berms and a geomembrane liner. The lowest price for a 30 mil PVC geomembrane was in a rectangular shape, with a single factory seam along the long axis of the rectangle. Using the maximum width possible with this liner, three retaining ponds were constructed in series using a single piece of geomembrane 4.6 by 20 m. Each retaining pond was approximately 4 by 4 m square.

The groundwater was pumped from the excavation wells into the retaining ponds, then allowed to flow over the surface as it cooled and underwent freeze separation. A slight natural slope at the site was used to create a gradient along the bottom of the retaining ponds, with the discharge outlet along the uphill edge. The water flowed as a stream across the retaining pond until it pooled at the lowest point, where ice and brine separated. Initially, the outlet was placed approximately 2 m above the pond liner, so that the water splashed into several streams when it struck the pond surface. To simplify sampling, the discharge outlets were later moved to ground level.

5.5.3 Sampling procedures, storage and reporting

Monitoring and sampling A simple sampling procedure was planned for the demonstration project. Samples of outlet groundwater were taken at irregular intervals to ensure that the pumping rate and the measured EC were constant. Samples of concentrated effluent brine and purified ice were taken from the pond during and at the conclusion of the test. Liquid samples were allowed to freeze for transportation back to cold storage at the University. Ice samples were also transported frozen to cold storage.

EC was measured in outlet samples as a surrogate measurement of the concentration of salt in the groundwater. Only a small amount of the total volume of contaminated groundwater was planned to be removed, so it was anticipated that there would not be any change in EC of the groundwater source during the project. A significant decrease in EC would have indicated preferential flow within the contaminated zone, as less-contaminated groundwater was transported along fissures or more permeable layers from outside of the plume to the wells.

5.5.3.1 Calibration of EC meter

Most regulatory limits for sodium and chloride levels in water are given as a maximum concentration (Health Canada, 1999; Alberta Environment, 1999). However, the regulatory limit may be expressed as a maximum EC (Oil Sands Wetlands Working Group, 1999). As groundwater typically contains some amount of dissolved solids, a background EC level should be expected. At sites contaminated by road salts, the increase in EC from the background level is a reliable measurement of the relative level of contamination. Because groundwater from a particular site will have a characteristic composition of dissolved chemicals, EC measurements must be calibrated to the groundwater before a site-specific relationship between conductivity and brine concentration can be developed (Hem, 1982). Conductivity is non-linear with high concentrations of sodium and calcium chlorides, but at concentrations commonly found in contaminated groundwater can initially be assumed to be linear. As a surrogate measure of concentration of dissolved chlorides from road salt contamination, measuring EC can be a rapid field test to replace or supplement more precise laboratory testing, and as a control variable for an automated process control system.

To develop the site-specific calibration for the Obed site, a series of EC measurements were taken using two fluids: distilled water and groundwater sampled upstream from the Obed site. The experimental procedure for developing this site-specific relationship is detailed below:

1. An Oakton Model 35607-10 pH/CON10 EC meter with a low-range probe (model 35607-99) was calibrated using commercially prepared KCl standard solutions: 1.413 mS/cm and 2.764 mS/cm.
2. Two sets of samples with various known concentrations of de-icing chemical sold for highway maintenance were prepared (see Table 5.6). One set had sodium chloride dissolved in distilled water, and the other used liquid calcium chloride mixed into distilled water. EC was measured for each concentration of each set. The calcium chloride liquid was a commercial product supplied by Tiger Calcium Service Inc. of

Edmonton, composed of 30% calcium chloride plus 3.5% magnesium chloride (by weight) in water. (Magnesium chloride is a naturally occurring component of the calcium chloride deposits used to produce this product.)

3. Using groundwater taken up-gradient from the Obed site, the same amount of road salts were added as for each of the two distilled water samples, and EC was measured for each sample.
4. The measurement error of the EC meter was determined by repeated measurements of several samples. The EC probe was washed with distilled water and placed in the solution until the EC meter stabilized. The probe was removed, washed with distilled water, then placed in the solution for the next measurement. Table 5.5 shows the results of this estimation of error for four solutions of varying concentration. A trend in the measurement error was observed, that the measured EC increased with the number of measurements. While the EC meter has an automatic temperature adjustment, there was no correlation between change in solution temperature and the change in measured EC. In the range of measured EC values for salt concentrations used in the calibration, measured EC error is approximately 2%, and judged not significant.
5. The four series of measurements were plotted. The difference between the EC of the distilled water and the EC measured in the Obed groundwater is the effect of the naturally occurring dissolved chemical background species.

Table 5.6 gives the results of the EC calibration. Although EC is often assumed to have a linear relationship to concentration, the actual relationship is non-linear over large ranges of concentration (Hem, 1982). Figure 5.8 shows a non-linear plot for the site specific calibration of EC to concentration of dissolved salts used during the demonstration project. Note that this calibration was not extended to the maximum concentration possible at very low air temperatures; and the local calibration would have to be confirmed if freeze separation treatment is planned at low design temperatures. The EC meter used has an automatic temperature correction, but no attempt was made to determine the error from using this automatic correction when testing field samples at temperatures near freezing. Future calibration should be carried out with fluid temperatures as close as possible to the actual conditions, in order to remove this possible source of measurement error.

5.6 Conduct of the demonstration project

Initial site preparation included building sand berms for the temporary retaining ponds, installing the geomembrane liner, and setting up the heated work trailer prior to and on 12 February, 2001. Pumping of contaminated groundwater at the Obed site was started at 14:00 hours on 12 February and continued at a constant rate until 16:30 hours on 15 February. Groundwater was extracted from two wells, 98 - 1 and 99 - 9A, at the maximum rate possible with the peristaltic pumps (0.15 L/min or approximately 0.25 kg/[s m]) for a total of 670 litres per well. There was no measurable drawdown at this rate, and groundwater level remained constant during the whole time that groundwater was being extracted.

Three temporary retaining ponds were constructed on the gravel pad surface, with berms built up from loose sand. The decision to use sand to construct the berms was made to simplify winter construction and clean up. Approximately 20 m^3 of sand were used to construct the berms. Typical dimensions of the berms were 1 m wide at the base, 0.4 m high and 0.3 m at the top. The berms were built using a front-end loader in less than one hour, and clean up took only slightly longer. Only a minor amount of hand labour during construction was required to give the berms their final shape. The base of two of the ponds was on a slight natural angle, and the third pond used a thin layer of loose sand to create a sloped bottom for natural flow from the tubing outlet. The liner was spread by hand and held in place by sandbags. Sampling was done from the edge of the pond.

Electrical power at the site was provided by a 50-kilowatt (kW) portable diesel generator. The generator powered two peristaltic pumps, the electrical heating cable and a space heater and lights inside the work trailer. Total power draw for all of these items was about 12 kW. This generator was very much larger than was required; a 20 kW generator had been reserved, but the rental agency delivered a larger one. Other than slightly higher operating costs (i.e., higher fuel consumption) with the 50 kW generator, there was no effect from using the larger generator.

The Geotechnical Centre of the Department of Civil Engineering, University of Alberta provided a work trailer for the demonstration project. This insulated trailer provided a secure, heated site to store equipment during the conduct of the work. While the trailer provided a comfortable workspace, its primary purpose was to prevent the peristaltic pumps from freezing. Use of a submersible pump would eliminate the need for heated space. The PVC tubing remained flexible throughout the testing period, and there were no problems with leaking or freezing.

It was planned to pump groundwater from three wells. Two of the wells, 99-9A and 98-1, were at the same ground elevation as the retaining ponds, and pumping from these wells was conducted as planned. The wellhead of the third well, 99-10A, was approximately 3.0 m below the retaining pond, with the groundwater table 1.5 m below the wellhead. The peristaltic pumps in the heated trailer were 1.0 m above the retaining pond, so the elevation head from well 99-10A was approximately 5.5 m. The peristaltic pump did not have adequate suction to overcome this elevation head difference, so well 99-10A was not used as an extraction well during the demonstration project.

A tarp was placed over a framework of logs above the retaining ponds, to prevent falling snow from diluting the brine produced during treatment. The reinforced plastic tarp was able to handle moderate snow accumulations but blew down in high winds the night of 13 February. When using freeze separation to treat groundwater, the decision on the use of covered retaining ponds must be made based on the expected amount and weight of snowfall and the size of the retaining ponds. Sites where heavy snowfalls are expected, or where large ponds are required, should probably have covered ponds during treatment.

The effluent brine was collected for disposal in a municipal landfill; the landfill operator granted permission because the volumes produced in the demonstration project were small. The temporary retaining ponds were removed and the site cleaned up during mid-winter. The ice layers were broken up with hand tools, and the ice and loose sand from the berms were transported back to the Hinton highway maintenance yard, where the sand was stockpiled for use once the ice had melted. The geomembrane retaining pond liner was salvaged for future use, and all signs of the fieldwork were removed by the end of March. Since the retaining ponds were built without excavating into the existing soil, there was no difficulty in cleaning up during the winter.

5.6.1 Regulation of outlet groundwater temperature

The PVC tubing was surface laid from the extraction wells to the retaining pond. To reduce the risk of freezing, the tubing was covered by commercially available pipe insulation with a commercially available electric heating cable inside the insulation. Electrical tape was used to hold the insulation in place over the tubing. The heating cable is sold at hardware stores to prevent the freezing of downspouts and eavestrough, it is available in a variety of lengths and delivers approximately 16 W/m. Groundwater temperature at the tube outlet varied with air temperature and the length of electrical heating cord powered. To reduce the temperature increase in the line, the heating cord over approximately half the length of each tube could be unplugged.

Using rough estimates from the field trial, approximately half of the heat from the cable was lost to the surroundings through the foam insulation, and half was absorbed by the groundwater as it flowed through the tubing. The optimal operating conditions would be for the groundwater to be discharged with a temperature just above freezing. This would ensure that groundwater started to freeze separate a quickly as possible while preventing the formation of ice in the tubing or fittings. Tubing with a different thickness, diameter or material will have a different rate of heat gain. As discussed in Chapter 4, it is recommended that a remediation project using freeze separation have a automated control system to reduce the pumping rate when air temperature is warmer than the design temperature; it would be a simple matter to also control the electrical heating cables and thus the groundwater outlet temperature using the same process control system.

Appendix 5 shows photos from site setup and operation.

5.7 Results of the demonstration project

5.7.1 Verification of the effectiveness of freeze separation

There were obvious indications during the demonstration project that freeze separation was effectively separating and concentrating the dissolved road salts in the extracted groundwater. EC measurements of effluent brine samples were higher than the EC measured at the groundwater outlet. Visual inspection of the ice showed an obvious change across a vertical cross section. Ice crystals became larger and the ice less dense (as determined by the difficulty in breaking off samples) when moving down from the surface, with a indistinct boundary layer of slush between the brine and ice layers. At the completion of pumping, the retaining ponds were left overnight when temperatures dropped to –24 °C. At this temperature, a sodium chloride solution would be in solid form at any concentration, while a calcium chloride brine would still be liquid. The brine layer was thinner than expected in the morning, and the slushy boundary layer less distinct. There was still a visible difference in the density and texture between the top and bottom of the ice; this was interpreted as a change in the rate of ice crystal formation at very high dissolved salt concentrations. From these observations, it should be expected that the concentration of contaminants would be higher at the lower levels of the ice, which was confirmed by laboratory analysis.

Laboratory tests of samples taken from wells 99-9A and 98-2 on 16 February are shown in Table 5.7. The preparation of samples for laboratory testing included blank and duplicate samples, with all results as expected with one exception. By mistake, the initial series of tests did not include a groundwater outlet sample for well 98-2. Duplicate samples were prepared for later testing, but the results had higher than expected concentrations of chlorides and TDS, indicating that there may have been problems preparing these later samples or inconsistent results from testing at a different laboratory. Possible sources of this error include separation of the sample when it was frozen for storage, contamination during sample preparation for testing or during handling at the laboratory. While this apparent sample testing error eliminates half of the results from analysis, it does not change the conclusion that freeze separation can be a valid groundwater remediation treatment.

Figure 5.9 shows the variation in EC measured in the groundwater and effluent brine during testing. The lower outlet EC values at the beginning of the test can be attributed to dilution of natural groundwater within the well by the distilled water used to prime the tubing during setup. From Figure 5.9, it is apparent that the concentration of dissolved road salts in the groundwater did not change significantly during the demonstration. As expected, effluent brine concentration was seen to be a function of air temperature, and independent of the initial concentration of the groundwater being treated. Using the site specific calibration and measured EC of the final effluent brine sample, the concentration of chlorides would be predicted as 8,880 mg/L for a calcium chloride solution, and 4,210 mg/L for a sodium chloride solution. Because the groundwater contamination is a mixture of sodium and calcium chloride road salts (see Section 5.3), the site specific calibration gives a reasonable estimate of the actual salt concentration when compared to the laboratory sample measured at 5,790 mg/L.

5.7.2 Experience gained to develop guidelines for the future use of freeze separation

Extraction well location The extraction wells used for the demonstration project were the observation wells previously installed for the Phase II and III ESAs. The wells were not located at the most heavily contaminated portion of the contaminant plume, and groundwater with an higher initial concentration could have been removed for treatment if new wells have been installed. This was acceptable for this demonstration project, but a full-scale remediation project would most likely require that the extraction wells be located to draw from the most heavily contaminated zone.

Extraction rate The peristaltic pumps used in the demonstration project had a maximum pumping rate of 0.15 L/min, or a mass flow rate per unit width of approximately 0.25 kg/[s m]. This rate is much lower than would be possible for groundwater extraction from most aquifers, and a higher pumping rate would have been used during the demonstration project if the pumps could have produced it. The peristaltic pumps used in the demonstration project did not produce the pressure head required to extract groundwater from well 99-10A as planned. The capacity and type of pump chosen for future remediation projects should be chosen after the maximum pumping rate has been calculated.

Monitoring The demonstration project did not use continuous monitoring. Future remediation projects should consider the use of an automated process control system to monitor effluent brine concentration and air temperature, in order to achieve maximum effectiveness from the freeze separation treatment. At the very least, effluent brine concentration should be measured when it is removed for disposal, as an indication that the treated water will meet the remediation target concentrations.

Preventing freezing during extraction At a flow rate of 0.15 L/min and a tube diameter of 10 mm and length of 40 m, the transit time from extraction well to retaining pond was approximately 20 minutes. The electric heating cable prevented the water from freezing in air temperatures that ranged from 0° to -26° C. In fact, the groundwater reached the retaining ponds anywhere from 2 to 14° C above its natural 2° C in-situ temperature. Because the groundwater temperature at the outlet varies with the amount of heating cable energized and air temperature, the specific energy contained by the groundwater as it entered the retaining ponds also varied. This increased the time required for the groundwater to form effluent brine, and would reduce the effectiveness of freeze separation treatment at higher pumping rates. As discussed in the previous section, it is recommended that future freeze separation projects have a automated process control system to adjust the power to heating cables so that the groundwater temperature at the outlet is constant and near 0 °C.

Freeze separation mechanism The intention during the demonstration project was to produce freeze separation in thin film flow over an ice surface, as discussed in Chapter 4. This was achieved during the first few hours of operation. Ice was observed to form in thin layers on the bottom of the retaining pond, below a thin layer of brine. Photographs in Appendix 5 confirm that this freeze separation mechanism can be effectively used for separation and concentration of dissolved road salts.

The temporary retaining ponds were built with a minimum of preparatory earthwork, and the slope on the bottom of the ponds was several degrees more than was required for open laminar flow. As discussed previously, the groundwater outlet temperature was significantly above 0 °C from the heat added by the electrical heating cables. Because of the steeper slope and warm initial temperature, the groundwater flowed a longer distance in heat exchange regime 1 than predicted. After 12 –14 hours of operation, sufficient water had collected in the retaining ponds to form a pool and reduce the distance the groundwater could flow. Once this happened, the warm groundwater cut through the ice and flowed into the pool before entering heat exchange regime 2. As a result, the freeze separation process went from thin film flow over an ice surface to ice formation above a liquid pond for the rest of the demonstration project. The ice that had formed below the effluent brine in the first few hours of pumping became the upper layer of ice above the brine layer, with new ice formation between the ice and brine layers.

The use of freeze separation in thin film flow over an ice surface was found to be more difficult to maintain during field operations than expected, especially compared to freeze separation by ice formation over ponds. More experience will be required before freeze separation in thin film flow over an ice surface can be considered as 'robust' a mechanism as spray freezing or ice formation over ponds.

Retaining pond covering The plastic tarps that were set up over the retaining ponds were adequate for light winds and snowfall, but failed in high winds during a snowstorm. Future projects will require a stronger structure to support a retaining pond cover.

5.8 Analysis of data from the demonstration project

During the literature review, it was apparent that there is no standard method to calculate the effectiveness of freeze separation. Several references give a figure for the percent of salts removed, but did not indicate how this was calculated (Elmore, 1968, Fetuck, 1968, Jean *et al.*, 1999, Parker *et al.*, 2000). Fertuck (1968) developed a relationship between the concentrations of sodium chloride in brine and ice, and the temperature gradient in a ice layer. This relationship used the ratio of salt concentration in the ice to salt concentration in the brine as a dimensionless parameter. No other references were found that defined how the effectiveness of freeze separation could be calculated. The following equations are proposed for future research and assessment of the effectiveness of freeze separation treatments:

Percent removal can be calculated as:

$$\%\text{removal} = \left(1 - \left(\frac{\text{total mass of salt in ice produced}}{\text{total mass of salt in groundwater extracted}}\right)\right) * 100\% \qquad [5.1]$$

Percent increased concentration can be calculated as:

$$\%\text{concentration} = \left(\frac{\text{concentration in brine}}{\text{concentration in ice}}\right) * 100\% \qquad [5.2]$$

As discussed in section 5.7.1, the results of the laboratory testing of samples from Well 98-1 have been eliminated due to a suspected sample preparation error. Table 5.8 shows the % removal and % increased concentration calculated for TDS and chloride concentration for the samples from well 99-9A. Note that the concentrations in the ice layer were taken as the average of the upper and lower ice samples; the actual percentage removal and concentration can be expected to increase as the ice thickness increases, and the effect of brine separation in the lower layers of the ice has less effect. As no estimate of the error in laboratory testing was made, only two significant digits are shown in table 5.8. Laboratory testing of more samples could increase the precision of the percent removal or concentration calculations, but this is unlikely to be of practical importance for assessing the effectiveness of remediation treatment by freeze separation.

5.9 Conclusions from the demonstration project

The conclusions that can be made from the demonstration project at the Obed Maintenance site in February 2001 are:

- Sufficient evidence was collected to show that freeze separation can be an effective ex-situ treatment for contaminated groundwater.
- Freeze separation by thin film flow over an ice surface was shown to be an effective technique, but more experience is required to resolve operational issues with how this technique can be maintained for long periods.
- Freeze separation by ice formation over water was shown to produce effective brine separation.
- An automated process control system for groundwater extraction and measurement of effluent brine concentration and outlet temperatures is recommended for future freeze separation projects.
- Pumps used to extract groundwater should be selected for both capacity and pressure head required.
- The use of electric heating cable and tube insulation was shown to effectively allow groundwater to be transported to retaining ponds in freezing temperatures for treatment, but had to be adjusted periodically to reduce high groundwater inlet temperatures.
- Using loose sand to construct berms for a temporary retaining pond allowed easy construction even after the ground was frozen.
- A cover over the retaining ponds must be strong enough to withstand extreme weather conditions

- Equations for percent concentration and percent removal were proposed, for use in future freeze separation research and remediation projects.

Table 5.1 Hydraulic gradient at Obed Maintenance site

Date	Magnitude of hydraulic gradient	Direction of Gradient (degrees from True North)	Wells used for Calculations
17 August 2000	-0.14 m/m	21	98-2, 99-9A, 99-10A
28 September 2000	-0.12 m/m	22	98-2, 99-9A, 99-10A
12 February 2001	-0.16 m/m	9	98-1, 99-9A, 99-10A

Table 5.2 Groundwater level (using assumed reference point) at Obed Maintenance Site

Date	Well 99-9A (m)	Well 99-10A (m)	Well 98-1 (m)
17 August 2000	96.7 m	94.0 m	97.2 m
28 September 2000	96.7 m	94.3 m	96.2 m
12 February 2001	95.7 m	93.4 m	95.7 m

Table 5.3 Groundwater sampling test results from selected wells at Obed Maintenance site (from Green Plan Limited 2000)

Test	Regulatory Limit	Well Sampled	Result
PH in water	Between 6.5 and 8.5 and within 0.5 of background [AEP]	99-9A	7.2
		98-1	7.1
		99-10A	7.4
Total Dissolved Solids	500 to 5,000 mg/L for agricultural use, varies by use [OSWWG]	99-9A	5900 mg/L
		98-1	4870 mg/L
		99-10A	3470 mg/L
Electrical Conductance	<2.0 mS/cm [OSWWG]	99-9A	10.40 mS/cm
		99-9	16.70 mS/cm
		98-1	9.42 mS/cm
		99-10A	6.40 mS/cm
Chloride (Cl)	Max 860 mg/L [USEPA]	99-9A	3040 mg/L
		98-1	2800 mg/L
		99-10A	1880 mg/L
Sodium (Na)	< 200 mg/L [HC]	99-9A	1900 mg/L
		98-1	1570 mg/L
		99-10A	710 mg/L
Calcium (Ca)	[No regulatory limit, HC]	99-9A	314 mg/L
		98-1	373 mg/L
		99-10A	460 mg/L
Cyanide, Total	0.2 mg/L [HC]	99-9A	0.024 mg/L
		98-1	0.030 mg/L
		99-10A	0.021 mg/L

Regulatory limits set by Alberta Environmental Protection (AEP), Canadian Council of Ministers of the Environment (CCME) and the United States Environmental Protection Agency (USEPA) taken from Alberta Environment, 1999. Regulatory limits for Health Canada, Environmental Health Directorate (HC) taken from Federal-Provincial Subcommittee on Drinking Water of the Federal – Provincial Committee on Environmental and Occupational Health, 1999. Suggested limits from the Oil Sands Wetlands Working Group (OSWWG) taken from Oil Sands Wetlands Working Group, 1999.

Table 5.4 Hydraulic conductivity measured at the Obed Maintenance site

Well Number	Screen depth and soil layer tested	Depth of water in well (m)	Time to remove 10 L groundwater for test (s)	Hydraulic Conductivity (cm/s)
98-2	98.7 to 92.5 m elevation; clay till, sand & gravel lenses, clay and sand pockets	6.0	120	7.0 x10^{-5}
99-9A	97.4 to 94.7 m elevation; sand till	1.1	240	4.2 x10^{-4}
99-10A	95.1 to 91.8 m elevation; sand and sand till	1.5	155	5.0 x10^{-5}

Table 5.5 Determination of EC Meter measurement error

Solution	Measured EC (mS/cm)	Solution Temperature (°C)	Average (mS/cm), and deviation from the average (%)
Distilled Water	0.035	23.4	Avg.: 0.034
	0.034	23.6	(+) 2.0 %
	0.034	23.7	(-) 0.9 %
	0.034	23.7	
Tap Water	0.262	22.4	Avg.: 0.284
	0.287	22.2	(+) 2.8 %
	0.286	22.0	(-) 7.7 %
	0.292	22.0	
	0.291	22.0	
1.413 mS/cm Standard Solution	1.084	22.3	Avg.: 1.097
	1.090	22.2	(+) 1.2 %
	1.096	22.2	(-) 1.2 %
	1.104	22.1	
	1.110	22.1	
15.0 mS/cm Standard Solution	14.27	21.9	Avg.: 14.624
	14.57	21.8	(+) 2.1 %
	14.66	21.8	(-) 2.4 %
	14.69	21.9	
	14.93	21.7	

Table 5.6 Results of EC calibration of Obed site groundwater

Concentration of salt added (mg/L)	EC in Distilled Water using Calcium Chloride (mS/cm)	EC in Obed Groundwater using Calcium Chloride (mS/cm)	EC in Distilled Water using Sodium Chloride (mS/cm)	EC in Obed Groundwater using Sodium Chloride (mS/cm)
5,000	16.87	17.30	9.42	10.69
2,500	8.94	9.98	4.17	4.85
1,000	3.90	5.26		
500	2.05	3.53	0.93	1.37
250	1.05	2.67	0.53	1.17
100	0.44	2.11	0.24	1.04
50				
20				0.96
10			0.03	0.94
5			0.02	0.93
0	0.02	1.75	0.01	0.91

Table 5.7 Laboratory analysis of samples from the Obed site demonstration project, February 2001.

	Well 99-9A		Well 98-1	
Location	Chlorides (mg/L)	TDS (mg/L)	Chlorides (mg/L)	TDS (mg/L)
Background concentration outside contaminated zone	413	1,000	413	1,000
Groundwater at outlet	3,940	7,310	678	1,600
Top of ice layer	1,560	2,590	728	1,330
Bottom of ice layer	1,540	2,810	973	1,880
Brine underneath ice	5,790	11,000	3,940	6,730

Table 5.8 Calculation of effectiveness of freeze separation from the Obed site demonstration project, February 2001

	Well 99-9A
% Removal of chloride concentration	32 %
% Removal of TDS	38 %
% increased concentration of chlorides in effluent brine	370 %
% increased concentration of TDS in effluent brine	410 %

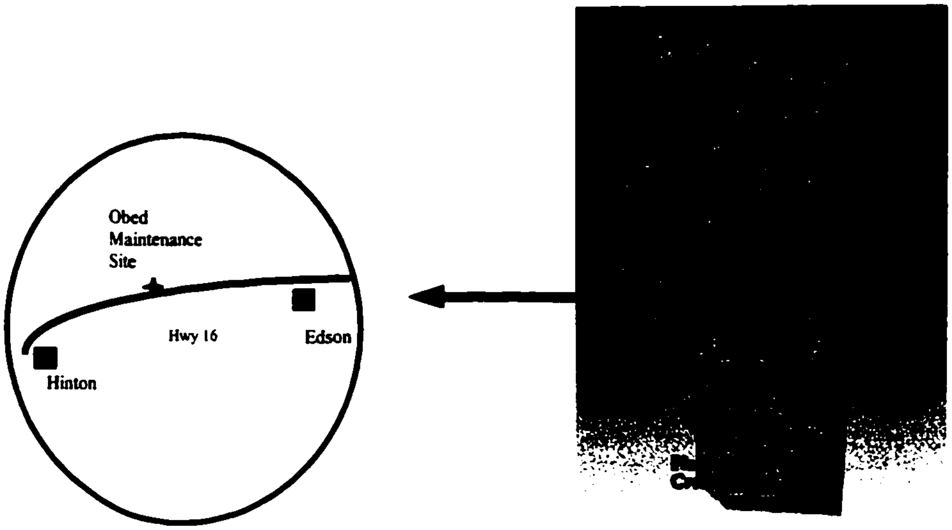
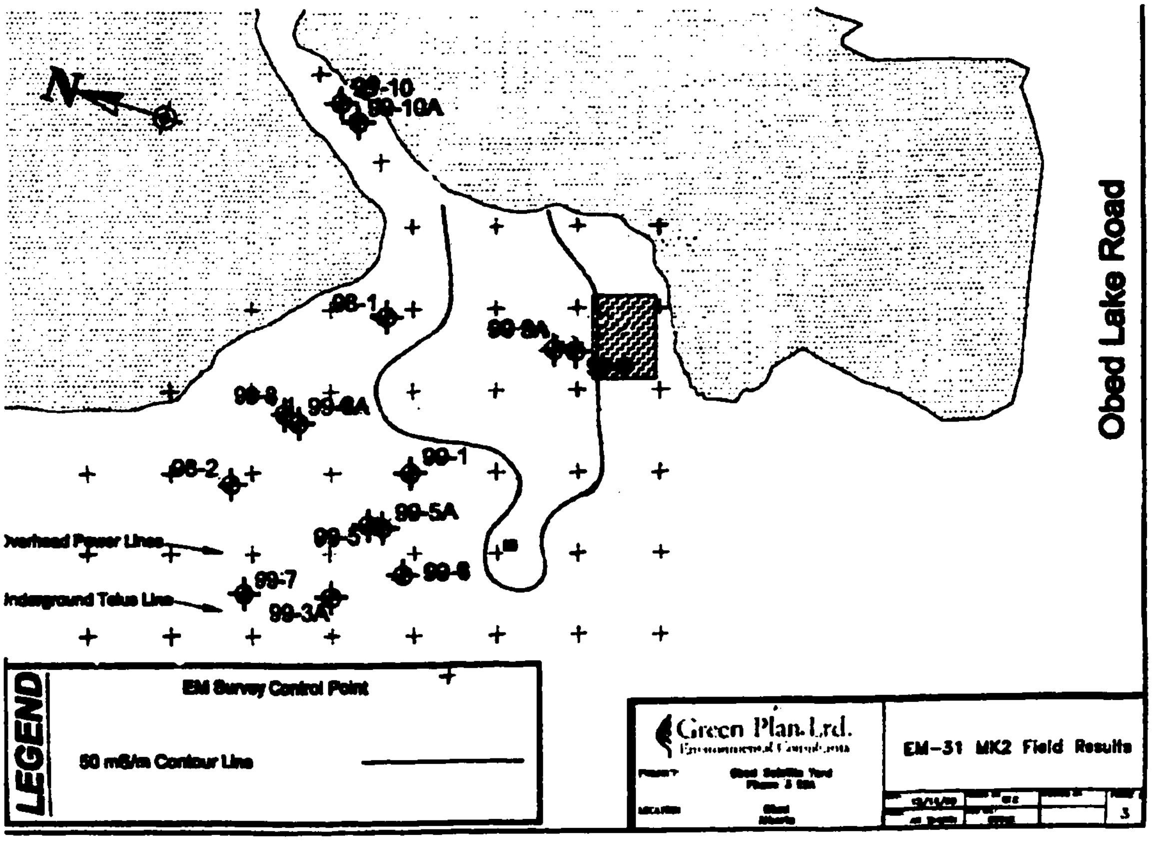
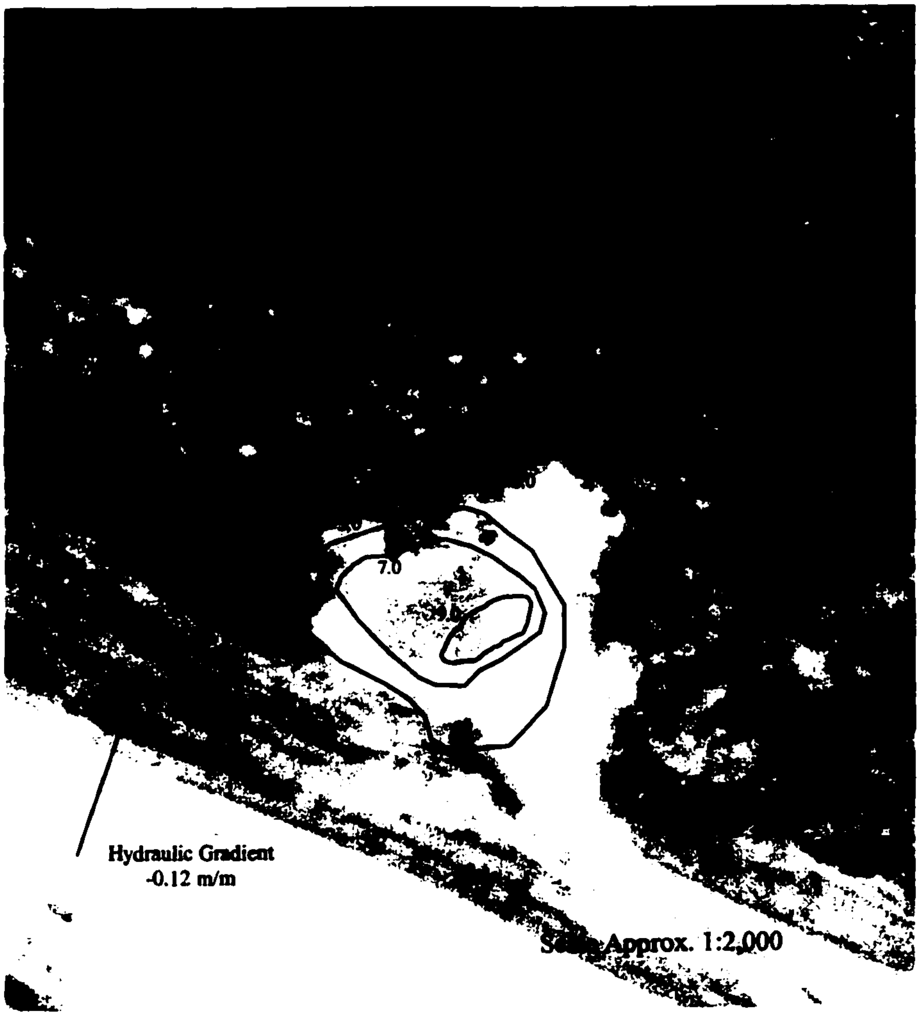


Figure 5.1 Location map



(from Green Plan, 2000)

Figure 5.2 Electromagnetic conductivity survey of Obed Maintenance site conducted by Green Plan Ltd., November 1999



(contours in mS/cm)

Figure 5.3 Electromagnetic conductivity survey of Obed Maintenance site conducted as part of preliminary site investigation, August 2000

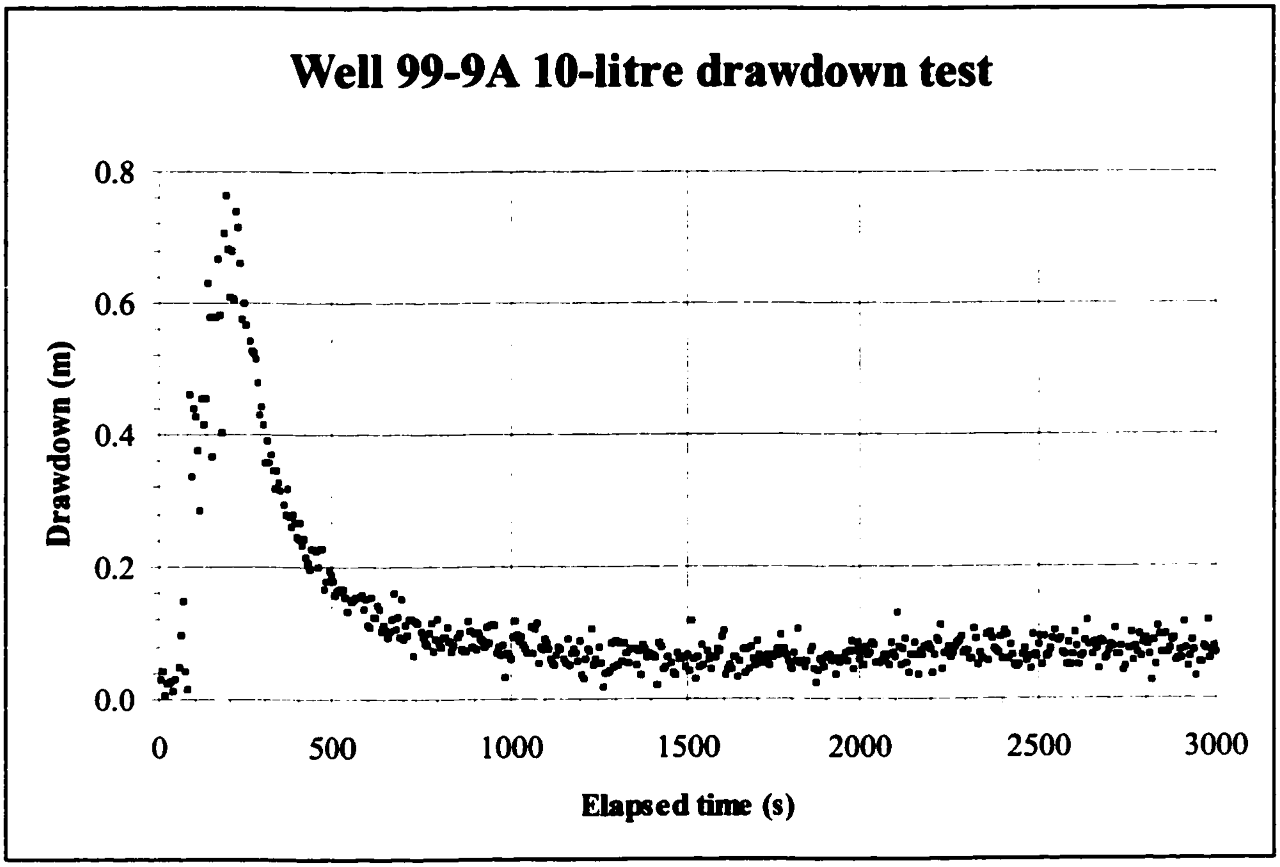


Figure 5.4 Drawdown test results from well 99-9A, showing the amount of scatter in automatically recorded data

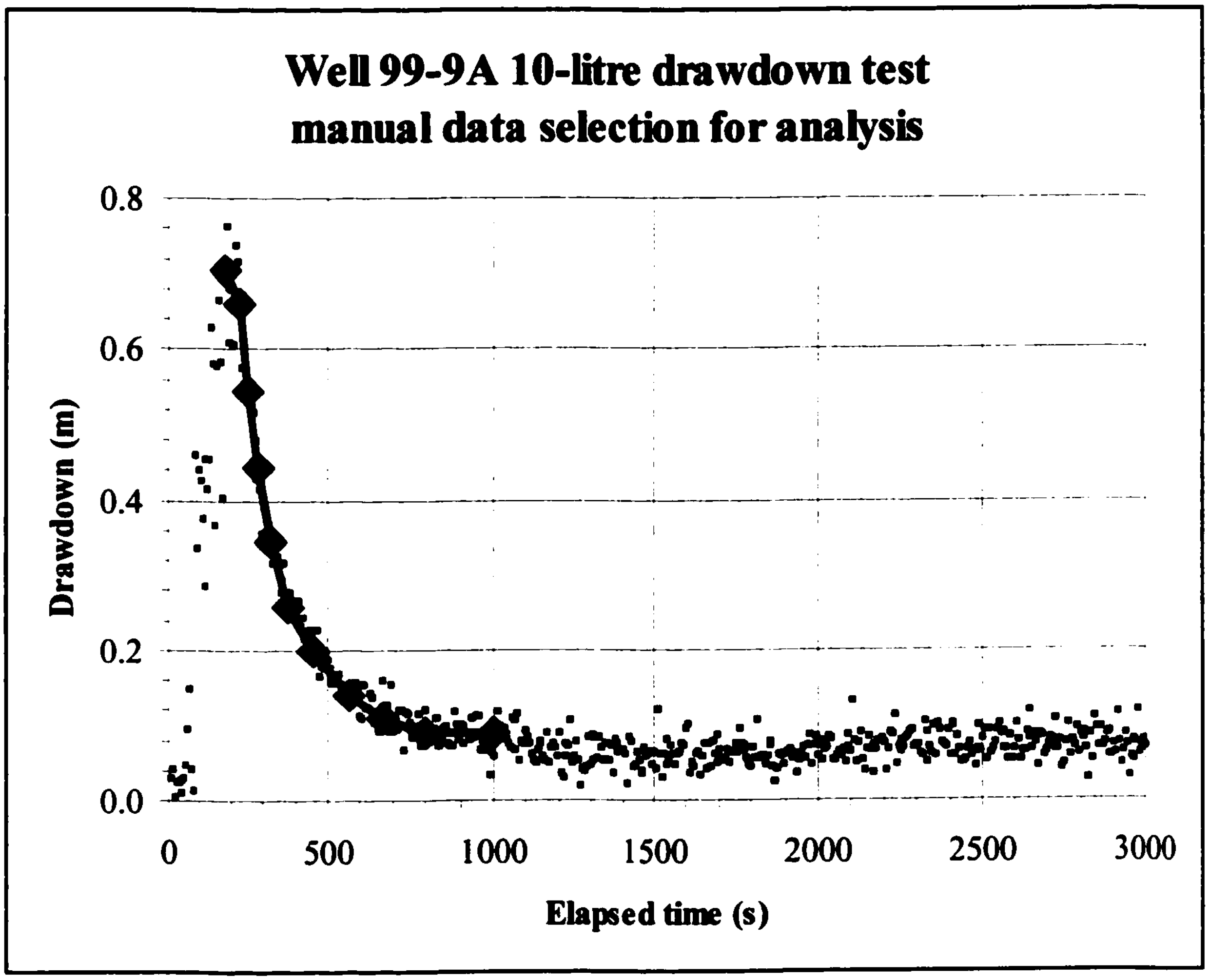


Figure 5.5 Example of manual selection of data points from 10-litre drawdown test, well 99-9A

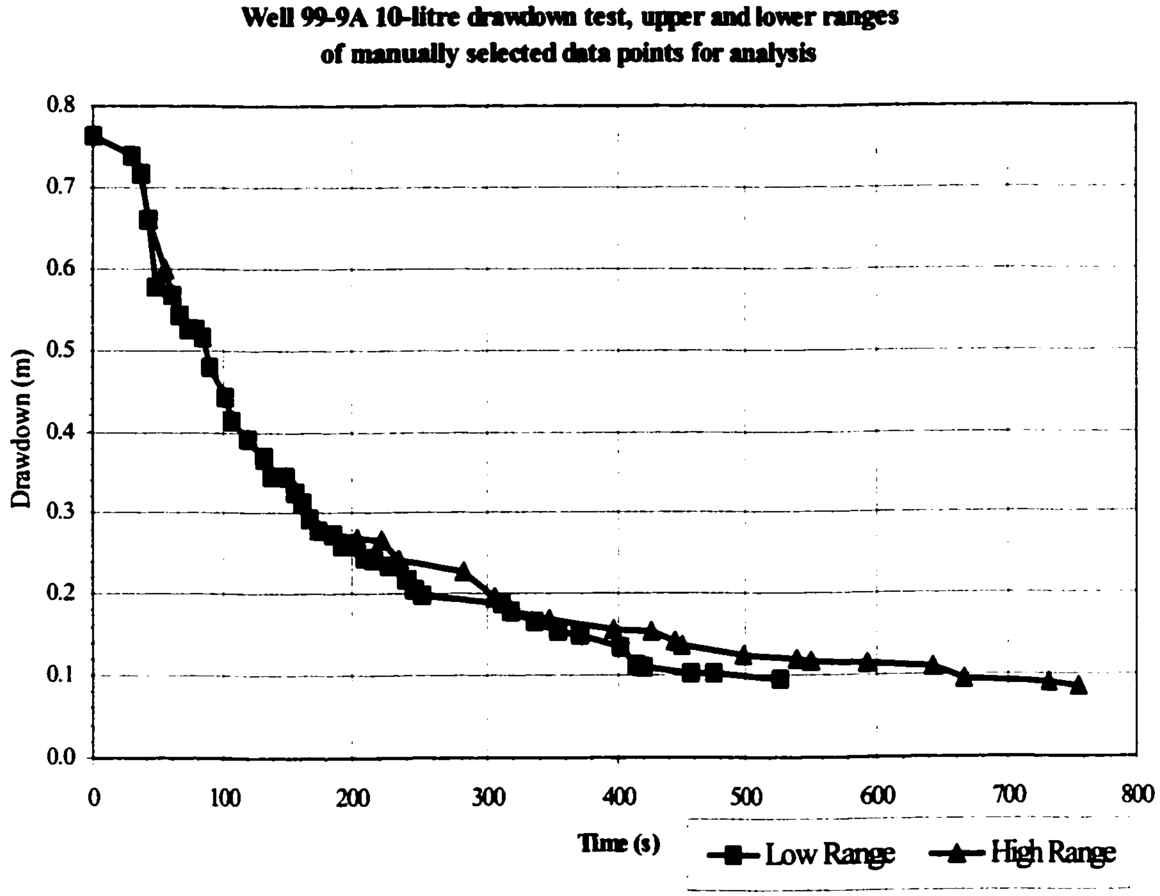


Figure 5.6 Evaluation of error using manually selected data points from drawdown tests, well 99-9A

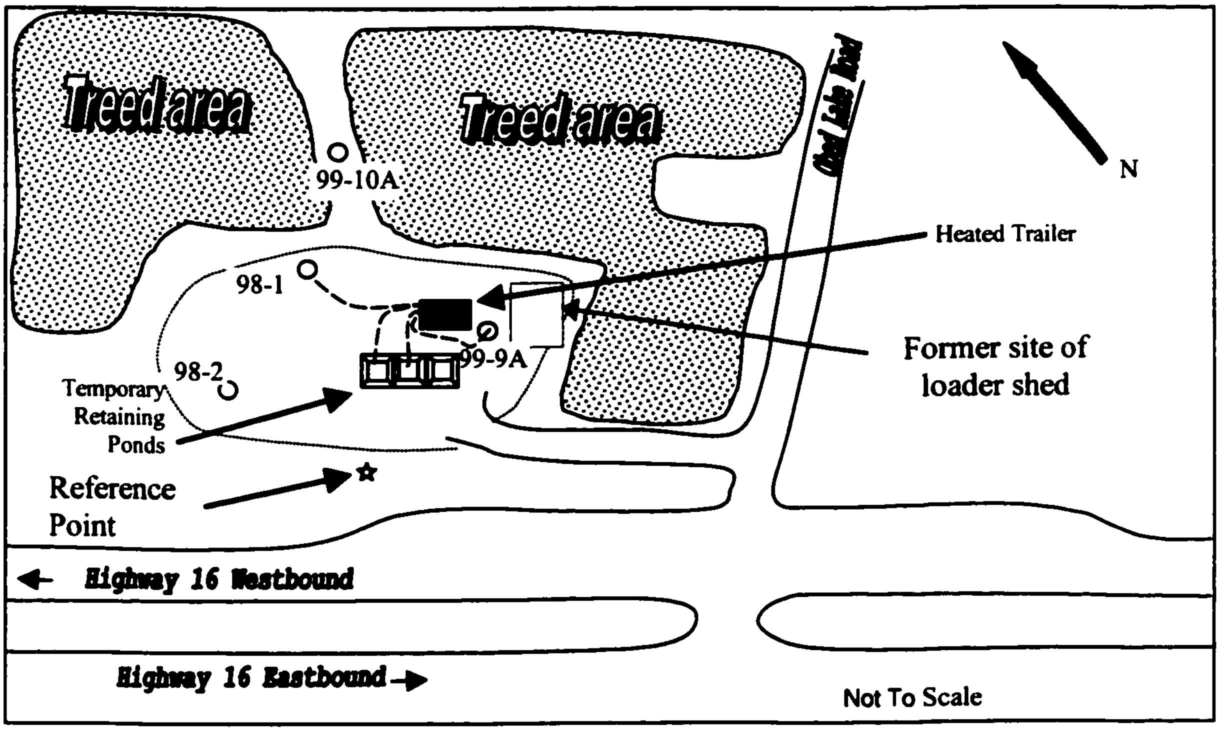


Figure 5.7 Site plan of the demonstration project, February 2001

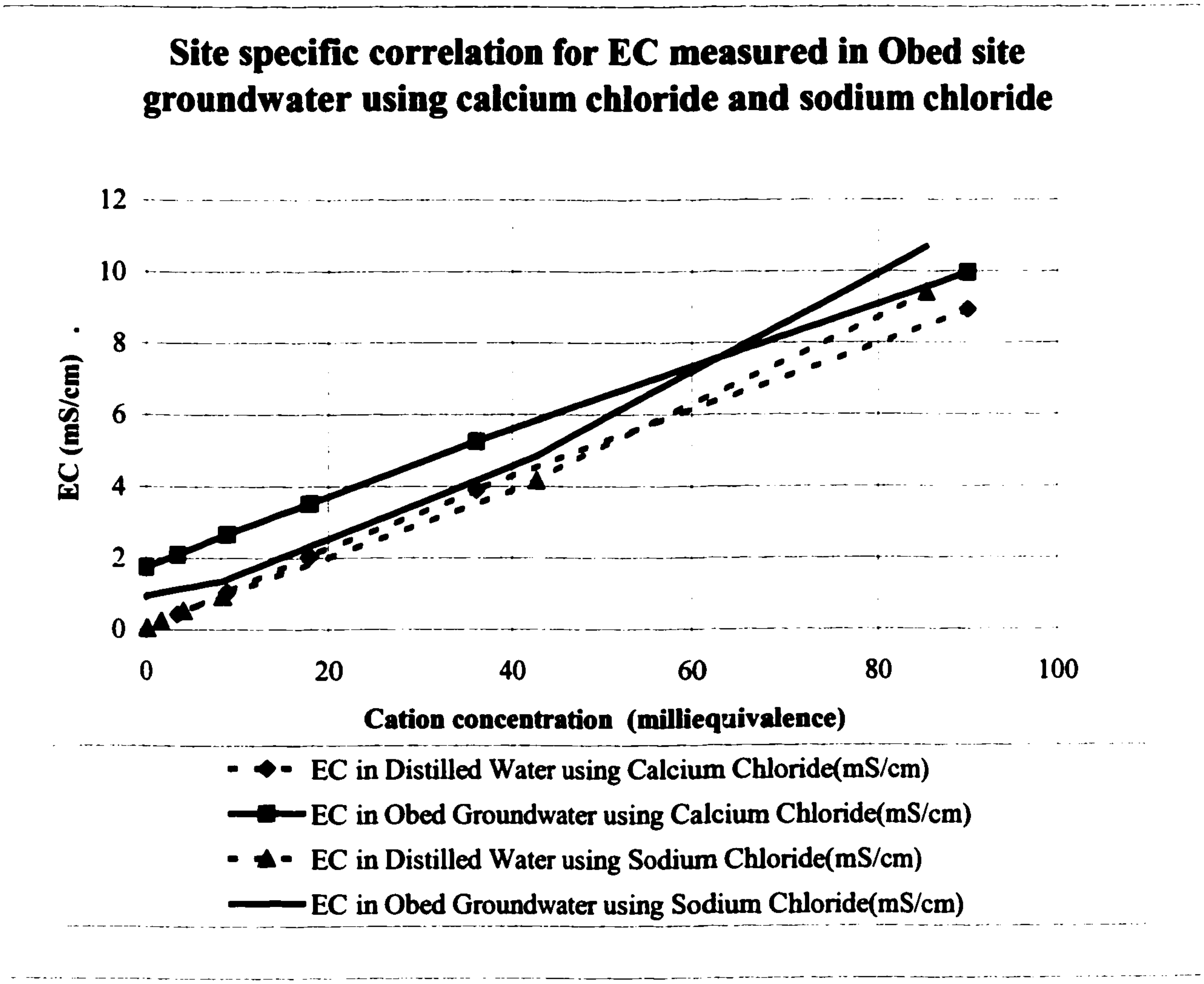


Figure 5.8 Obed site specific EC relationship for sodium chloride and calcium chloride dissolved in groundwater and distilled water

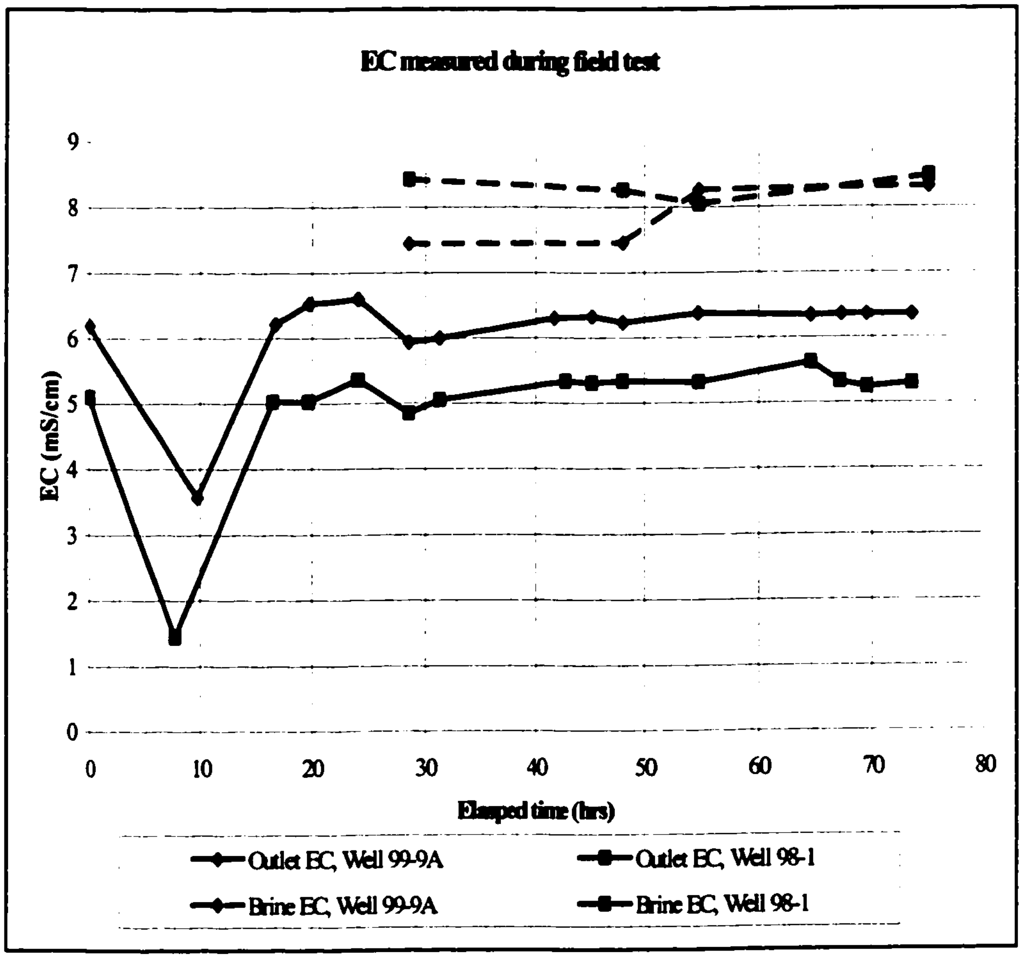


Figure 5.9 Measured EC in outlet groundwater and effluent brine during the demonstration project

Chapter 6

PRELIMINARY EVALUATION OF FREEZE SEPARATION FOR TREATMENT OF CONTAMINATED GROUNDWATER

In normal practice, detailed planning of groundwater remediation projects begins with a feasibility analysis of several possible treatment options (often as part of the Phase III ESA). Because freeze separation has not been used as a remediation technique previously, there are no case studies for review to help determine the viability of freeze separation as a treatment option for remediation projects. This chapter proposes a methodology and scoring system for the preliminary evaluation of the suitability of freeze separation as a treatment option at a particular site. If the results of the preliminary evaluation indicate that freeze separation may be a viable option, then a detailed site design and cost estimation can be done in order to compare it with other possible treatment options. If the preliminary evaluation indicates that freeze separation is not apt to be a feasible treatment, then no further analysis is required. The factors that will influence this evaluation are discussed in Sections 6.1 and 6.2, followed by details of the evaluation procedure in Section 6.3. This preliminary evaluation was developed for evaluation of freeze separation of groundwater contaminated by road salts. Future research is needed to evaluate how well this preliminary evaluation process works and how it could be amended for evaluation of other groundwater contaminants.

To conduct the preliminary evaluation process, the remediation designer should know or confidently estimate parameters in two general categories: groundwater characteristics and site characteristics. The following guidelines were developed objectively using engineering judgment for typical conditions, and may be amended for evaluation of a particular site.

6.1 Freeze separation preliminary evaluation process; groundwater characteristics

Site characteristics that must be known for this preliminary evaluation are:

- Salt concentration in the contaminated zone (both above and below the groundwater table),
- Allowable concentration levels for the contaminant (legislated or the site specific remediation objectives),
- The volume of contaminated groundwater,
- The hydraulic conductivity for soils in and around the contaminated zone, and
- Soil structure (especially highly permeable layers, fractures and bedrock character)

In the range of road salt contaminant concentrations reported in Canada (Morin, 2000), all of the road salts will be fully dissolved in the groundwater. Some of the mass of salt dissolved in groundwater will have diffused into "dead end" or immobile pore spaces, and it is reasonable to expect a tailing effect as these salts diffuse back into the interconnected pore spaces filled by fresh groundwater as treatment proceeds. Constituent ion concentrations determined by laboratory testing of soil and water samples taken during ESA Phase II and III work should be used to determine an average salt concentrations above and below the water table.

Using the terms defined in Section 4.5.4, the percent recovery can be calculated as:

$$\text{Percent recovery} = m_{rem} / m_{tot} \quad [6.1]$$

where:

m_{rem} = mass of salt that must be removed by treatment (kg), and
m_{tot} = total mass of salt contaminating the site (kg)

The greater the percent recovery required, the more difficult it will be for treatment to succeed. Published references for other uses of freeze separation have reported that the effectiveness of salt removal is in the range of 70 to 95% for saline water. Sites that require a smaller percent recovery are suitable for treatment by freeze separation, since less of the salt present must be removed to achieve the remediation goals. The preliminary evaluation procedure will give the highest score to sites where the required percent recovery is below 75%, with a decreasing score as the percent recovery increases above 75%.

Actual soil conditions are rarely homogenous, and most sites are apt to have less permeable layers, lenses of other types of soil, or fractures that will result in preferential flow paths. The more homogenous the soil, the more uniform the flow through the contaminated zone, and the more effective will be extraction of the contamination. Another factor that will influence how effectively contaminated groundwater can be removed is the length of time since the contaminant was introduced. Where the salts were only recently released, most of the contaminated groundwater will be in fractures or zones of higher hydraulic conductivity. The longer the contaminant is present in the groundwater, the more it will have diffused into areas of lower hydraulic conductivity, and the more difficult it will be to remove by groundwater extraction. The preliminary evaluation process will give a higher score for sites with soils that are typically more homogenous, and that have been contaminated for only a short time.

Expenses for remediation by freeze separation will include mobilization/demobilization and operating/production costs. Since the energy to freeze the groundwater during winter is free, and the freeze separation process can be designed to require infrequent monitoring and intervention, the operating costs of freeze separation are apt to be lower than other remediation methods. Daily unit production costs will depend on the pumping rate and how much effluent brine is produced, and will not be affected by the total volume of groundwater treated. In contrast, mobilization expenses are less sensitive to the volume of groundwater to be treated, influenced only by the incremental costs for larger pumps and retaining ponds. Since the mobilization costs must be recovered by the total volume of effluent brine produced, remediation projects that have small volumes of contaminated groundwater will not be as cost effective as projects that have much larger volumes of groundwater to treat. The preliminary evaluation process will give higher scores for sites that have larger volumes of contaminated groundwater.

Of the three groundwater characteristics discussed above, the percent recovery is considered roughly twice as important as the soil type or the volume of groundwater recovered.

6.2 Freeze separation preliminary evaluation process; site characteristics

While groundwater characteristics primarily influence the effectiveness of freeze separation, site characteristics influence cost effectiveness. Parameters for site characteristics are:

- availability of electric power supply on site,
- distance from a disposal facility for the contaminant,
- average cost for local labour,
- distance of the contaminated site from all weather road, and
- local land use (existing and future)

Material and labour costs for construction and operation of the freeze separation treatment, effluent brine disposal costs and power costs are all site specific and have a direct effect on the total cost of remediation. The land use classification of the site is considered in the development of site-specific remediation guidelines using the risk-based approach, but not for sites operating under generic guidelines (CCME, 1996). Since treatment by freeze separation is unlikely to remove all of the contamination from the site and not all sites will develop site-specific remediation guidelines, the risk to future land users should be considered during the evaluation. Freeze separation involves off-site disposal of the effluent brine, so the distance to an all-weather road will have an important impact on the ease of the remediation operation during the winter. Of the site characteristics, local labour costs and land use have the greatest effect on costs, followed by the proximity to an all-weather road. The source of electrical power, and distance to the brine disposal facility have the least relative importance to costs. Site characteristic parameters do not require further data manipulation or calculation.

6.3 Scoring groundwater and site characteristics

These scores have been developed based on the considerations discussed above using engineering judgment. They are not unique and can be modified based on experience. Figures 6.1 and 6.2, and Table 6.1 are used for the scores of groundwater characteristics at a site. Site characteristics are scored using Table 6.2. Once the groundwater and site characteristic scores have been determined, Figure 6.3 is used to assess the potential of freeze separation as a remediation treatment at the site.

6.4 Examples of preliminary evaluation of freeze separation

<u>Example 1</u>: A former maintenance satellite stockpile site is located 2.5 km on a gravel road from the main highway in an undeveloped, forested area of northern Alberta. This site has been in operation for the past 20 years as a source for sand and gravel for road construction and maintenance. The stockpile site is located over sandy- silty sand and gravel fluvial deposit with a high water table. Site investigation indicates that the average salt concentration in the groundwater under the stockpile site is 25,000 mg/L in a contaminated zone of 50 m^3. Preliminary plans are to extract at least 200 m^3 of groundwater in order to adequately flush the soil. The maximum allowable concentration after treatment is 5,000 mg/L. At 25,000 mg/L in 50 m^3, 1,250 kg of salt are contaminating the site. At the maximum allowable concentration after treatment, 250 kg

of salt can remain at the site, so at least 1,000 kg of salt must be removed by treatment. Using equation [6.1], the percent recovery is 1,000/1,250 = 80%.

The site characteristics are that there is no permanent power supply to the site, it is 42 km to the nearest brine disposal facility, the average local cost for casual labour is $22.50 / hr, distance from an all-weather road is 2.5 km, and the local land use is for forestry/recreational.

The score for the preliminary evaluation is shown on Figure 6.4. The preliminary evaluation indicated that this site is recommended for use of freeze separation.

Example 2: Salt contamination of groundwater under the adjacent property has been identified as being from a highway maintenance yard operated by municipal government. The facility is located on a paved local road in rural farming area, with the nearest development a farm residence and domestic water well 500 m away.

The average groundwater table is within 1 m of the ground surface during the year, in a clay till with clayey - sandy layers with very low hydraulic conductivity overlain by a thin (450 mm) topsoil layer. This maintenance facility has been in operation for 30 years in the same location, with salt storage for the entire time. Site investigation has determined that the average salt concentration in the groundwater is 55,000 mg/L, and that the volume of contaminated groundwater is 50 m^3. At 55,000 mg/L in 50 m^3, approximately 2,750 kg of salt are contaminating the site. Municipal regulations require that remediation treatment achieve a reduction in contaminants to drinking water standards; so the allowable concentration after treatment is 500 mg/L. The mass of salts to be removed by treatment from the 50 m^3 of groundwater is thus 2,725 kg. Using equation [6.1], the percent recovery is 2725/2750 = 99%.

The site characteristics are: there is electrical power on site, it is 260 km (one way) to the nearest brine disposal facility, the casual labour costs at this unionized site is $26.40 /hr, it is 200 m from the far end of the site where the maximum contamination has been identified to the paved road, and the land use of the area surrounding the maintenance yard is agricultural.

The score for the preliminary evaluation is shown on Figure 6.5. The preliminary evaluation indicated that this site may be suitable for use of freeze separation, but that further cost estimation and detailed remediation design will be required to make the final judgement.

Table 6.1 Scoring soil type and duration of contamination

Contaminated soil type	Score if contaminated less than 3 years (points)	Score if contaminated more than 3 years (points)
Sand or sandy gravel	20	15
Silty sand or silty gravel	15	10
Silt or organic silts	5	2
Clay, organic clays, clayey sand or silty clays	2	0

Table 6.2 Scoring site characteristics

Site Characteristic	Detail	Score
Electrical power supply	Power grid	10
	Portable generator	5
Distance from brine disposal facility (one way)	25 km	10
	25 to 50 km	6
	50 to 100 km	4
	100 to 150 km	1
	> 150 km	0
Average cost local labour (per hour, including personal vehicle)	< $15	30
	$15 to $25	26
	$25 to $35	10
	> $35	0
Distance to site from all weather road (one way)	< 1 km	20
	1 to 3 km	15
	3 to 5 km	10
	5 to 10 km	5
	> 10 km	0
Site Land use classification (existing and future)	Industrial	30
	Forestry/Recreational	23
	Agricultural/Commercial	7
	Residential	0

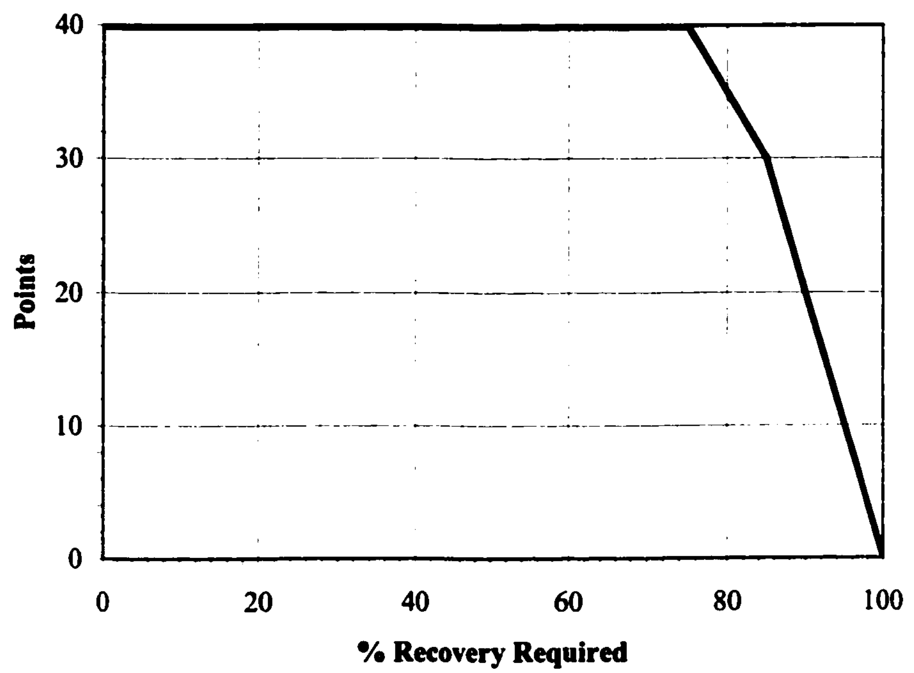


Figure 6.1 Scoring Percent Recovery

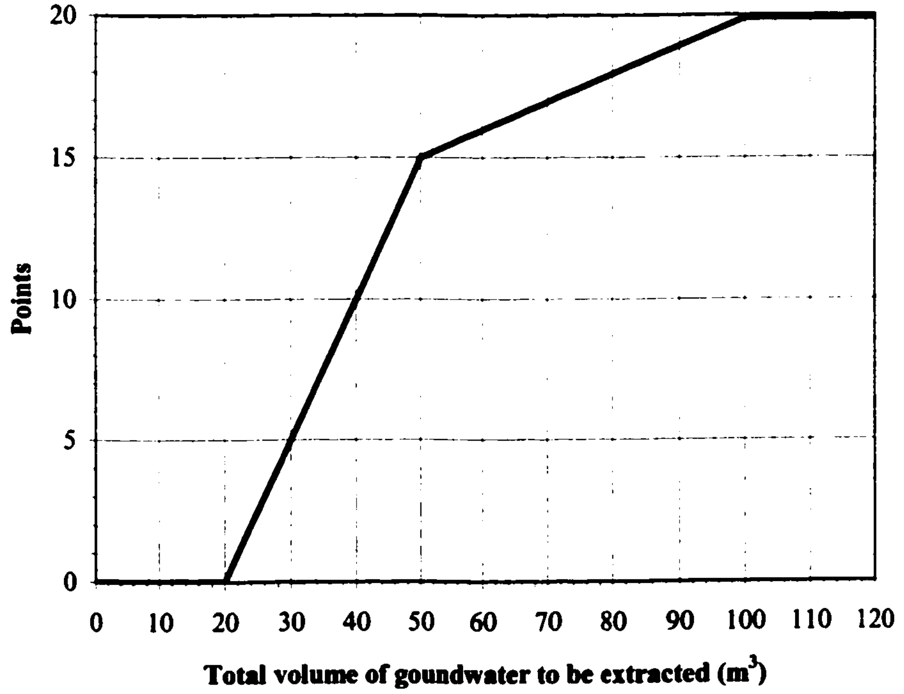


Figure 6.2 Scoring quantity of groundwater extracted

Groundwater Characteristics Score:

1. Percent recovery required Score:
2. Soil type and length of time contaminated Score:
3. Volume groundwater extracted Score:

Groundwater Characteristic Total Score: ☐

Site Characteristics Score

1. Power supply on site Score:
2. Distance from contaminant disposal facility Score:
3. Cost of local labour Score:
4. Distance from all-weather road Score:
5. Land use Score:

Site Characteristic Total Score: ☐

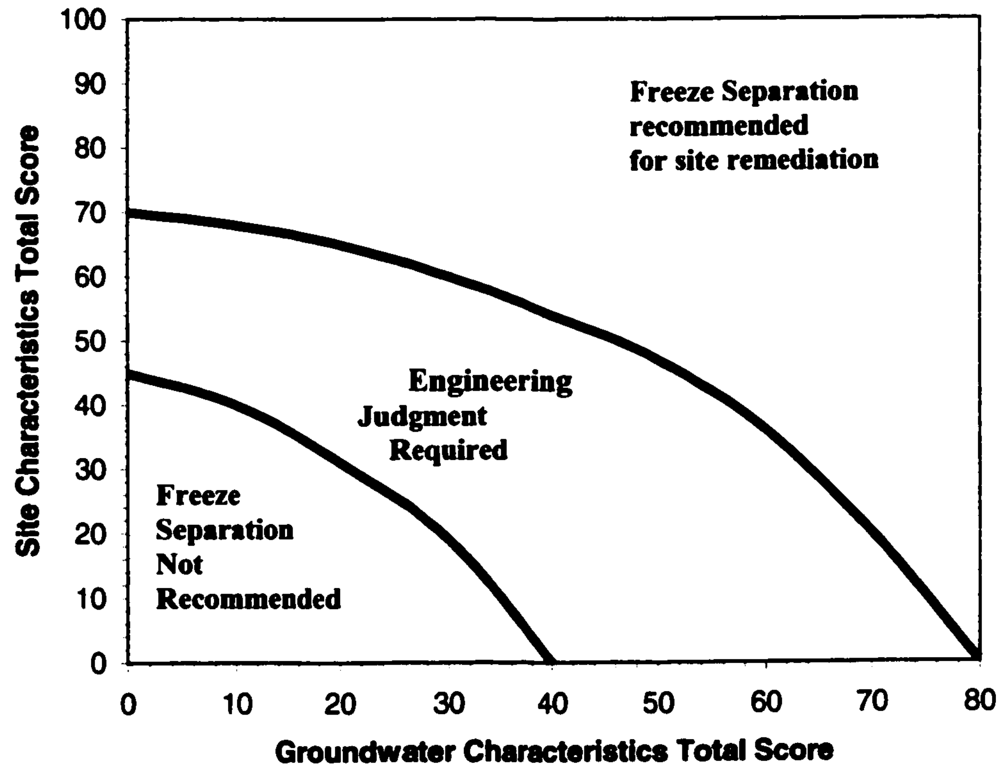


Figure 6.3 Preliminary evaluation scoring sheet

Groundwater Characteristics Score:

1. Percent recovery required	Score:	35
2. Soil type and length of time contaminated	Score:	10
3. Volume groundwater extracted	Score:	20

Groundwater Characteristic Total Score: 65

Site Characteristics Score

1. Power supply on site	Score:	5
2. Distance from contaminant disposal facility	Score:	6
3. Cost of local labour	Score:	26
4. Distance from all-weather road	Score:	15
5. Land use	Score:	23

Site Characteristic Total Score: 75

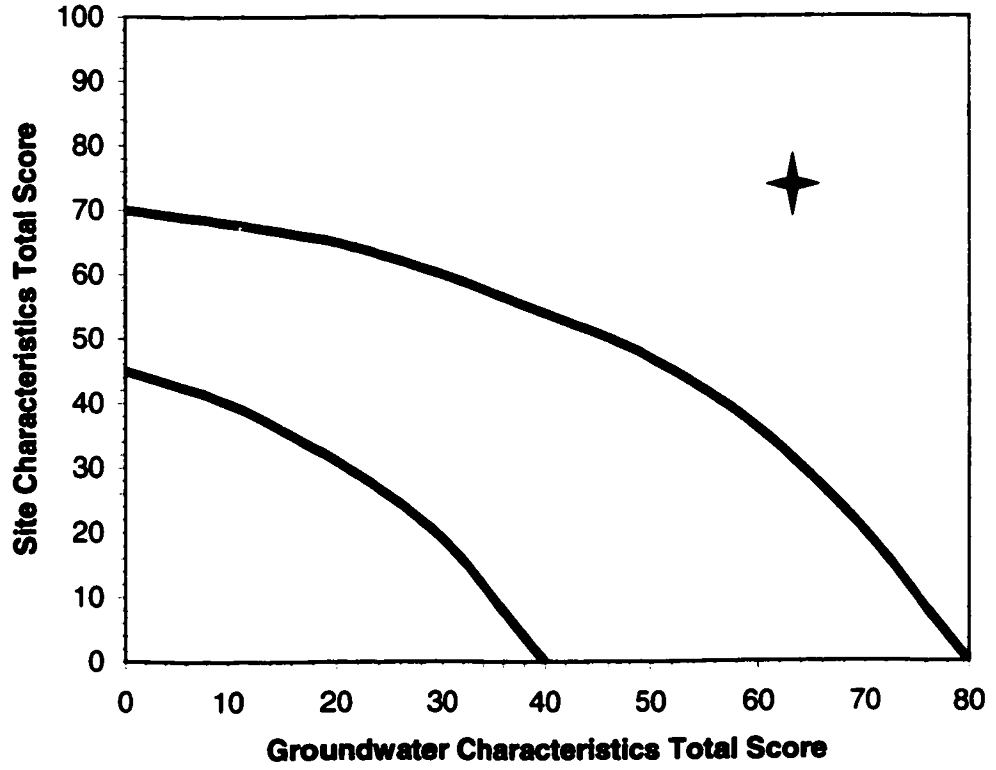


Figure 6.4 Example 1 Preliminary evaluation scoring

Groundwater Characteristics Score:

1. Percent recovery required	Score:	0
2. Soil type and length of time contaminated	Score:	0
3. Volume groundwater extracted	Score:	25

Groundwater Characteristic Total Score: 65

Site Characteristics Score

1. Power supply on site	Score:	10
2. Distance from contaminant disposal facility	Score:	0
3. Cost of local labour	Score:	10
4. Distance from all-weather road	Score:	20
5. Land use	Score:	7

Site Characteristic Total Score: 47

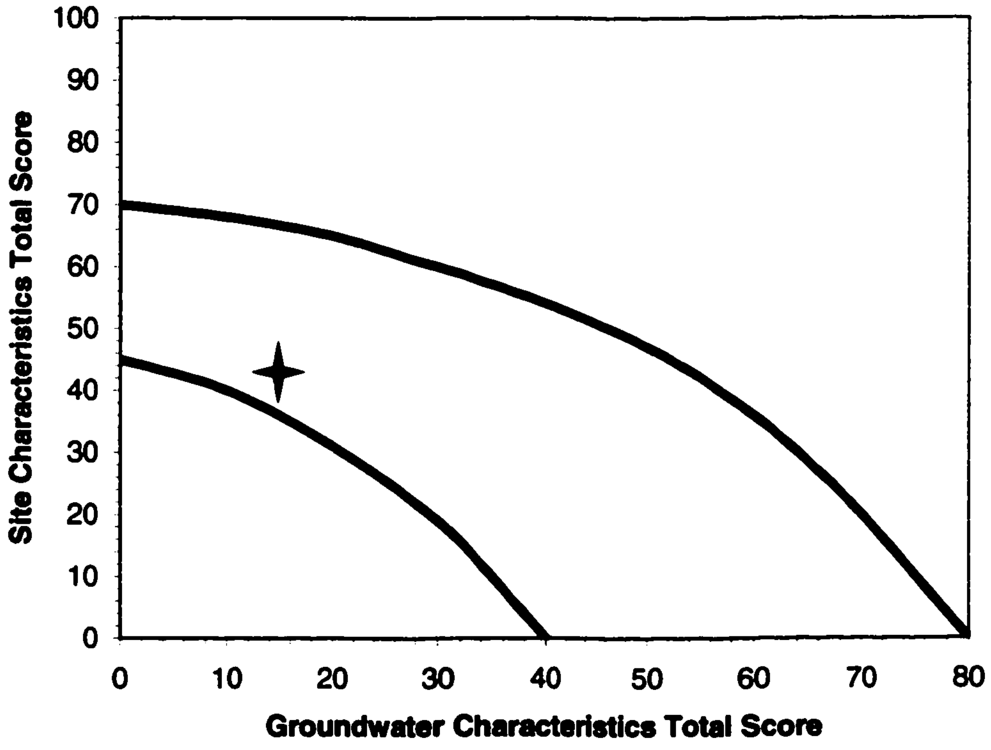


Figure 6.5 Example 2 Preliminary evaluation scoring

Chapter 7

COST ANALYSIS OF FREEZE SEPARATION

7.1 Cost of the 2001 demonstration project

The pilot scale field project completed in February 2001 was designed to minimize costs while still demonstrating the simplicity of the treatment. Direct cost of the field project was $4,900. This cost is not representative of a full-scale implementation. Some of the particulars of the field project that affected costs were:

- labour costs were not included in project expenses,
- groundwater was extracted from wells outside the heavily contaminated zone to increase the range of contaminant concentrations treated,
- peristaltic pumps were used to provide greater control over pumping rates,
- above-ground pumps required heated storage which would not be required when using submersible pumps,
- none of the materials used in the project were assigned a salvage value,
- some materials were provided at no cost by the University of Alberta,
- the generator used to supply electrical power had higher operating costs than were justified by the requirements of the project, and
- costs for effluent brine disposal were not included.

7.2 Estimating costs of freeze separation

In order to achieve the optimum remediation results, the site evaluation and soil quality guidelines should be developed before selection of the remediation technique (CCME, 1997). Evaluation of all techniques, including freeze separation as an ex-situ treatment, should be done after the site investigation has been completed. Costs associated with the site investigation should either be included in the evaluation of all treatment alternatives, or excluded from the evaluation. For freeze separation, extraction well(s) should be located near the center of the contaminated zone, and are usually installed as part of the site investigation. If a new well is required, its cost should be included with the estimate for treatment.

The four main categories of costs that must be considered when estimating the use of freeze separation on a particular site are:

- Site preparation costs,
- Material purchase costs,
- Operating and monitoring costs, and
- Site clean-up costs.

Each of these categories will be considered separately.

7.2.1 Site preparation costs

To estimate site preparation costs the following should be included as appropriate:

- Access to the site,
    - Are road improvements required? Will snow removal be required?
- Electrical power supply,
- Earthwork and facility construction,

  - Preparation of the work site. Are temporary structures required for materials storage? Will a heated workspace be required? Is surface drainage capacity sufficient for control of meltwater during operations, or for surface release of treated water (with regulatory approval)?
  - Protection from other contaminants at the site. Are there other contaminants present in the soil or groundwater? Will groundwater extraction mobilize other contaminants?
  - Construction of lined retaining pond
  - Construction of cover for retaining pond
  - Clear lanes through brush for temporary overhead power lines
- Site security,
  - Fencing
  - Security patrols
  - Vehicle access control
- Permits and approvals, and
- Public relations.

Three factors will have a major impact on site preparation costs. These depend on the choices to:

- Use a dugout or temporary above-ground retaining pond,
- Generate electrical power on site or draw from the power grid, and
- Cover the retaining pond.

Construction of a dugout retaining pond requires heavier earth-moving equipment and handling and storage of excavated soils than construction of an above - ground temporary pond using loose soil or sand berms. If the excavation is deep or the contamination shallow, an excavated pond may have to be moved away from on top of the contaminated zone, which would increase the space required and the amount and complexity of tubing. Advantages of an excavated retaining pond are simplicity of construction and the ability to place the pond on any slope. Advantages of a temporary ponds are that they only require a limited amount of earthwork (to level the bottom) and can be constructed in any shape and height. A disadvantage of a temporary pond is that it may be more expensive to haul in and remove the loose sand. A compromise would be to use the spoil from a shallow excavated pond to form berms above the ground level.

Electrical power is required by the extraction pump and heating cable, and possibly for lighting if night – time operations are anticipated. If the site already has electrical power, it should be a simple matter to install a temporary control panel for use during the treatment. If the site does not have power, the electrical utility can provide an estimate of the cost to install a temporary line. The cost of even a temporary line is affected by distance and route from the nearest grid connection, any brush clearing needed under the line, the anticipated power demand on site, and the local power rate.

If the surface area of the retaining pond is small, it may be cost effective to cover the pond to prevent snow from falling on the ice. Ashton (1980) discusses the reduced rate of heat transfer when there is a snow cover over ice, an important consideration if the extracted groundwater will be treated by formation of ice on a pool inside the retaining pond. As discussed in Section 4.5.4, it may be necessary to cover the retaining pond to shade the ice from the sun.

7.2.2 Material costs

To estimate material costs the following should be included as appropriate:

- General delivery charges for materials,
- Geo-membrane for pond liner,
- Framework and tarps to cover retaining pond,
- Tubing, fittings, and pumps,
- Electrical heating cable and insulation,
- Sand or gravel for berms in temporary retaining pond,
- Sandbags, and
- Instrumentation and cabling for monitoring treatment.

When estimating the cost of the geomembrane pond liner, the shape of the pond should be considered. Geomembranes that are less than 15 m wide may be delivered in an accordion fold package, while wider membranes will come in a roll. The equipment required to handle and spread the membrane may have a substantial affect on cost.

Automating the extraction pump with a control system that measures the concentration of effluent brine produced may reduce the need for human supervision of the site during treatment. The initial cost of a control system could be distributed over several treatment projects. A competent process control designer should be consulted to design and estimate the capital and operating costs of such a system.

7.2.3 Operating costs

To estimate operating costs, the following should be included as appropriate:

- Anticipated treatment time (including if the treatment and effluent brine disposal will include removal of the first meltwater in the spring)
- Labour costs,
- Travel time to the site and from the site to the brine disposal facility,
- Effluent brine disposal costs,
- Fuel costs,
- The need for pumps to be maintained at above freezing temperatures,
- Forecast of effluent brine production and removal schedule,
- Forecast rate of electrical power consumption, and
- Monitoring and testing requirements.

Based on the experience of this field project, the most likely time for mechanical problems is in the first few hours of treatment. After the equipment has worked without problems for several hours, there should be no need to have anyone on site except for periodic checks and to remove effluent brine for disposal. The amount of on-site supervision may also be affected by regulatory monitoring requirements.

7.2.4 Clean-up costs

To estimate clean - up costs the following should be included as appropriate:

- How much of the material and equipment used in treatment will be salvaged,
- Regulatory requirements for waste soil or ice left on site,
- Long-term monitoring requirements,
- Earthworks cleanup, and
    - pond removal
    - topsoil salvage and replacement
    - establishment of vegetative cover
    - surface runoff erosion control measures
    - spoil removal
- Final inspection costs.

The remediation objective concentration will have been determined based on the results of the site investigation, following a process similar to that outlined in CCME (1996). If the site clean up is delayed until after the frost is out of the ground, it may be necessary to use other equipment (i.e., tracked versus wheeled loaders) with lower productivity and higher total costs. Other costs associated with clean-up may include long-term monitoring of groundwater and effluent from the site, inspections by regulatory agencies, or topsoil recovery and long-term erosion control.

7.3 Typical unit costs for estimating

For initial cost estimating, the unit prices in Table 7.1 are based on Canadian dollar prices as of April, 2001.

7.4 Example Cost Estimates for Freeze Separation Treatment

Two examples of contaminated site treatment are given with initial cost estimates.

7.4.1 Example 1

A highway maintenance yard located just outside a small town has road salt contamination identified in a 5 m thick sand layer underneath 8 m of granular fill. The contaminated zone is underneath and immediately adjacent to a sand stockpile site. The water table is at the top of the silty sand layer. The entire contamination zone is contained within the site boundaries, and the site remediation is being funded by the municipal government owner. The owner will obtain all approvals. An Phase III ESA shows that the contaminated zone is approximately 500 m^3 in the silty sand layer only, with average chloride concentrations of 18,000 mg/L. The volume of contaminated groundwater is about 125 m^3. A pumping rate of 5×10^{-4} m^3/s (or 30 L/min) was planned from an existing 50 mm (diametre) well. In 10 days at 30 L/min, 430 m^3 will be extracted.

There is power and all weather vehicle access to the site at no additional cost. A monitoring well at the edge of the property can be used for long-term monitoring. The municipality has decided that a temporary retaining pond will be used in order to limit the impact on daily operations at the site during and after treatment, using a 30 mil PVC liner from a supplier 150 km from the site. A rectangular 20 m x 28 m temporary retaining pond using sand berms 1 m high will provide a capacity of 470 m^3 and require 110 m^3 of sand to construct. The sand is available from a commercial pit 10 km away. The effluent brine will be disposed in an oilfield waste injection well located 25 km away. The retaining pond is not covered. Table 7.2 gives the cost estimate for this example.

7.4.2 Example 2

Groundwater at a remote maintenance stockpile in southern Alberta was contaminated with salt water during operations, starting 35 years ago and continuing to the present. Following complaints by the adjacent landowners, a site investigation determined that the heavily contaminated zone is approximately 500 m^3 of fissured silty clay extending from the water table (0.3 m below the surface) to a depth of 6.5 m. The volume of contaminated groundwater is 100 m^3. Chloride concentrations in the contaminated zone average 12,000 mg/L with maximum concentrations of 35,000 mg/L. The area immediately around the wellhead is fenced to prevent entry by the adjacent landowner's cattle, but the fenced area is not large enough for a retaining pond. The landowner has given permission to construct a dug - out retaining pond providing that the water in it is suitable for agricultural use at the completion of treatment. A 30 mil PVC liner will be placed under a 0.3 m thick layer of gravel fill in the retaining pond. The supplier for the liner is 280 km away. All necessary approvals have been received for the site remediation and groundwater extraction. For the work to be completed in the current year, there are approximately 60 days of below freezing temperature available for pumping after site set-up. A pumping rate of 2 x 10^{-5} m^3/s (or 1 L/min) from a 50 mm extraction well. In 60 days at 1 L/min, only 86.4 m^3 will be extracted from one well, so at least two wells will be required.

Using two wells that bracket the contaminated zone and had been installed during the environmental site investigation, a total of 173 m^3 groundwater will be extracted for treatment. The retaining pond will be rectangular with a trapezoidal cross section, 8 m x 20 m x 1.2 m for a total volume of 180 m^3. The pond will not be covered. The PVC liner will be delivered accordion folded in thirds and no special equipment is required to place it. There is power and all weather vehicle access to the site at no additional cost. Brine disposal will be at a commercial oilfield waste disposal facility 45 km from the site. The contractor who is available to supervise the treatment will have a 60 minute one-way drive. Table 7.3 gives the cost estimate for this example.

Table 7.1 Unit costs for estimating

Treatment Phase	Description	Unit Cost
Site Preparation and Clean-up	(1) Retaining pond construction & clean-up	
	For Excavated pond: Bulldozer & operator for excavation (90 HP or equivalent @ 15 m^3 per hour)	$104./hour (1)
	For Temporary pond: Front end-loader & operator (50 m^3 per hour)	$68./hour (1)
	Laborer to assist equipment operator	$15/hour (6)
	(2) Electrical supply from power grid	$1,000 minimum plus $2,000/100m single phase line (2)
	(3) Supporting framework for covering the pond (labour only)	$4.60 /$m^2$ (3)
	(4) Truck haul soil and non-hazardous waste	0.20 /m^3 km (6)
Materials	(1) Retaining pond	
	Geo-membrane liner	$3.50 /$m^2$ (4)
	Delivery charge (if liner > 150 kg. For example, 30 mil PVC weighs 0.91 kg/m^2)	$1.30 /km (3)
	Sand for berms in temporary pond, delivered	$10/$m^3$ (6)
	(2) Tubing, filter sock, heating cable & insulation	$1.50/m tubing & fittings (5) $1.40/m heating cable (5) $0.20/m tube insulation (5)
	(3) Tarps and wooden supporting framework for pond cover	0.55/m^2 plastic tarp (5) plus $2.00/$m^2$ area covered by framework (3)
Operation and Monitoring	Labour to operate pumps & brine removal (with vehicle, including travel time)	$20/hour (6)

	Electrical power (1) From power grid (4kW single phase @ \$0.14/kW hour plus demand fees) (2) From 9 kW portable generator (including 45 litres of fuel per day @ 0.65/litre)	\$40/day (2) \$56/day (7)
	Laboratory testing (Chlorides content only)	\$13/sample (9)
	Haul brine to disposal facility	\$0.20 /m^3 km (6)
	Effluent brine disposal	\$20/m^3 (8)
	Submersible pump (18 litre per minute, 12 v DC, 4.5 A)	\$2/day (10)
	Not included: Miscellaneous materials such as sample containers, hand pumps, sandbags and hand tools, snow removal on access road, process control equipment or project management fees.	

(1) Alberta Roadbuilders & Heavy Construction 2000 Equipment Rental Rates Guide
(2) ATCO Electric (personal communication 5 May 2001)
(3) National Estimator© software, Craftsman Book Company, 2000.
(4) Nilex Inc. and Layfield Plastics (1978), Edmonton (personal communication Jan 2001)
(5) Home Depot Hardware, Edmonton, Jan. 2001
(6) Alberta Transportation Construction and Maintenance contract bid prices, 2000/2001 fiscal year
(7) Radar Rentals, Calgary, April 2001
(8) Canadian Crude Separators (personal communication, 9 April 2001)
(9) AMEC Laboratories, Edmonton, April 2001
(10) Jade Mountain Distributors, Colorado, April 2001

Table 7.2 Example 1 cost estimate

Treatment phase	Work	Cost
Site Preparation	1) Retaining pond construction 2.25 hrs front end loader and 1 laborer @ $83/hr	$ 187
	Truck haul sand 110 m^3 * 10 km = 1,100 m^3km @ 0.20	$ 220
Materials	1) Geomembrane 24 x 30 = 720 m^2 @ $3.5	$2,520
	Delivery charge 1.30/km * 150 km	$ 195
	2) Tubing, etc. 40 m @ $3.10/m	$ 124
	3) Labour to install geomembrane & tubing, 5 hours	$ 75
	4) 110 m^3 sand @ $10 / m^3	$1,100
Operation	1) Labour to check tubing, remove brine for disposal 1.5 hours per day for 10 days @ $20/hr	$ 300
	2) Electrical power for 10 days @ $40/day	$ 400
	2) Effluent brine disposal: Assume approximately 5% of extracted groundwater removed as brine = 2 m^3 per day @$20/$m^3$ plus 50 m^3km@ 0.20	$ 500
	4) Submersible pump for 10 days @ $2/day	$ 20
	5) 5 water sample lab tests at conclusion of treatment @ $13 each	$ 65
Clean-up	1) Remove retaining pond 2 hours loader plus laborer	$ 166
	2) Sand and ice haul back to pit, 500 m^3 for 5,000 m^3km @ 0.20	$1,000
Total	Treating 125 m^3 contaminated groundwater Estimated $55 / m^3 treatment cost	$6,872

Table 7.3 Example 2 cost estimate

Treatment phase	Work	Cost
Site Preparation	1) Retaining pond construction	
	90 hp bulldozer for 12 hours	$1,248
	16 man-hours labour during excavation, installing the PVC liner.	$ 240
	3) 80 lineal meters of 3-wire fence around pond @ 4.50/m plus gate	$ 400
Materials	1) Geomembrane 13 x 24 = 312 m^2 @ $3.5	$1,092
	Delivery charge 1.30/km * 280 km	$ 364
	2) Tubing, etc. 20 m @ $3.10/m	$ 62
Operation	1) Labour to check tubing, remove brine for disposal 3 hours per day for 60 days @ $20/hr	$3,600
	2) Electrical power for 60 days @ $40/day	$2,400
	3) Effluent brine disposal: approximately 5% of extracted groundwater removed as brine = 1 m^3 per 7 days (10 trips) @ $20/$m^3$ plus 45 m^3km @ 0.20	$290
	4) 2 Submersible pumps for 60 days @ $2/day	$ 240
	5) 4 water sample lab tests at conclusion of treatment @ $13 each	$ 52
Clean-up	General site clean-up, 4 man-hours @ $15/hr	$ 60
Total	Treating 173 m^3 contaminated groundwater Estimated $58 / m^3 treatment cost	$10,050

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions from evaluation of freeze separation as a remediation technique

A literature review indicated that there was no theoretical reason that freeze separation would not be an effective ex-situ treatment for groundwater contaminated by road salts. Freeze separation has been used in the past for the concentration of dissolved or suspended substances in a variety of industrial and municipal fluid streams..

As freeze separation has not been used for treatment of contaminated groundwater prior to this time, this thesis included the development of a planning sequence for freeze separation remediation projects, a calculation method for concentration of road salts in the treated ice and effluent brine produced by freeze separation, and a mathematical model to predict the distance that groundwater will flow across an ice surface until it has reached the maximum concentration possible by freeze separation. The demonstration project, at the Obed Maintenance site in February 2001, verified that freeze separation is effective in the treatment of salt-contaminated groundwater, and provided practical experience for the conduct of future remediation projects using freeze separation. Analysis of the results of the demonstration project include calculations for the percent removal and percent concentration produced by the treatment, which can be used in future research or remediation projects.

As an aide to the rapid and comprehensive evaluation of the suitability of freeze separation for future remediation projects, a preliminary evaluation process was developed that uses information available from a Phase III ESA report. The use of the preliminary evaluation will rapidly identify projects that are unsuited for use of freeze separation for geotechnical or economic reasons. Comprehensive parameters for cost estimation can be used for estimating the cost of future freeze separation project, for comparison with other remediation techniques. The conclusion of this evaluation of freeze separation for treatment of groundwater contaminated by road salts is that freeze separation can become a practical and effective option for remediation planning.

8.2 Recommendations for future research

While freeze separation could be used for groundwater remediation at any time in suitable sites, the following research would assist in its acceptance as a routine option in remediation planning:

1. Freeze separation should be compared to other groundwater remediation treatment options at several other sites with road salt contamination, to validate and further develop the proposed preliminary evaluation process.
2. A pilot scale test should be conducted, using an optimized design to validate or modify the proposed analytical design guidelines for freeze separation by thin film flow over an ice surface.
3. A contaminated site for full-scale freeze separation treatment should be chosen, and the results of treatment by freeze separation recorded and reported.

4. Research for the use of freeze separation treatment of other types of contaminant should be conducted. The proposed evaluation process should be assessed as a framework for the preliminary evaluation of freeze separation of other contaminants, and modified as necessary.

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Appendix 1: Calculation of significant length, as the sum of the lengths of two temperature regimes

Heat exchange regime 1: Groundwater cooling from outlet temperature to its freezing point temperature

During the first heat exchange regime, groundwater loses heat from its original outlet temperature to the freezing point of the liquid, when ice crystals begin to form. Heat is lost by convection to the colder air above, and by conduction to the ground below. The shortest distance in regime 1 (l_{s1}) will occur when groundwater temperature at the outlet is just above its freezing point; the warmer the groundwater is at the outlet, the longer the length for this regime. In-situ groundwater is typically only a few degrees above freezing (Bowen, 1980), but may be several degrees warmer at the discharge outlet if the groundwater has been heated in the tubing between the extraction well and the outlet. It is assumed that the temperature of the ground below the flowing water is constant, at the design temperature (T_{air}). This assumption is based on having the ground surface cooled to air temperature before pumping begins, and that the thermal mass of the ground is much larger than the thermal mass of the groundwater.

The energy balance model for heat exchange regime 1 per unit width is:

$$q_{specific} = q_{conduction} + q_{convection} \qquad [A1]$$

where: $q_{specific}$ = rate of specific energy loss (energy of enthalpy) (J/s m),
$q_{conduction}$ = rate of energy loss via conduction (J/s m), and
$q_{convection}$ = rate of energy loss via convection (J/s m)

The sign conventions for equation [A1] were adopted so that all energy levels are calculated as positive numbers. Assumptions made in developing this model are discussed in Section 4.6.

The rate of specific heat added with the groundwater is calculated as (Kinsky, 1977)

$$q_{specific} = \dot{M}\,\Delta H \qquad [A2]$$

where: $q_{specific}$ = rate of specific energy gain (energy of enthalpy) (J/s m),
$\dot{M}$ = mass flow of water per unit width (kg/s m), and
ΔH = enthalpy (J/kg).

The heat flow rate will depend on the difference between the groundwater temperature and air temperature. As the groundwater temperature in heat exchange regime 1 will vary between initial outlet temperature and the freezing point temperature, the average temperature in heat exchange regime 1 is:

$$T_{avg} = (T_{out} + T_l)/2 \qquad [A3]$$

where: T_{avg} = average groundwater temperature in heat exchange regime 1 (K),
T_{out} = groundwater outlet temperature (K), and
T_l = freezing point of the liquid (K)

Conductive heat flow rate per unit width from the fluid into the ice surface is calculated as (Kinsky, 1977):

$$q_{conductive} = \frac{k_t\left(T_{avg} - T_{air}\right)l_{sl}}{b} \qquad [A4]$$

where: $q_{conduction}$ = rate of energy loss via conduction (J/s m),
k_t = thermal conductivity (J/[m s K]),
assumed constant for water near 0 °C as 0.522 J/[m s K]
T_{avg} = average groundwater temperature in heat exchange regime 1 (K),
T_{air} = ground temperature, assumed equal to design temperature (K),
l_{sl} = length in heat regime 1 (m), and
b = thickness of boundary layer (m)

Energy transfer by conduction depends on the thickness of the boundary layer (see equation [A4]). Various references (Perry and Chilton, 1973; Kay and Nedderman, 1974; Drakos, 1994) give the equation for a two-dimensional model of boundary layer thickness for laminar flow with larger Reynolds numbers as:

$$b = C\sqrt{\frac{\nu\, l_{sl}}{u}} \qquad \text{[A5]}$$

where b = boundary layer thickness (m),
C = constant, given in different references as between 1.0 and 5.83,
ν = kinematic viscosity (m^2/s),
l_{sl} = length along direction of flow (m), and
u = velocity of flow (m/s)

The boundary layer thickness calculated using formula [A5] was 40% of the water layer thickness, which appears to be incorrect for the thin film groundwater flow being modeled, and a more reasonable estimation of the thickness of the boundary layer of 5% of the flowing water film thickness was assumed for the development of the heat flow rate model. The flowing water thickness is calculated as (Perry and Chilton, 1973):

$$B = \left[\frac{0.085\,\dot{M}\,\mu}{g\,\rho^2 \sin\phi}\right]^{1/3} \qquad \text{[A6]}$$

where B = flowing water film thickness (m),
$\dot{M}$ = mass flow of water per unit width (kg/s m),
μ = dynamic viscosity (kg/[m s]),
g = gravitational acceleration of 9.81 m/s^2,
ρ = density of groundwater (kg/m^3), and
ϕ = angle of slope on the bottom of the retaining pond of 0.2%.

Physical parameters for water (i.e., density, viscosity, specific heat) near freezing varies somewhat with temperature, as shown in Table 4.6. The value of T_{avg} was used to determine the values for these parameters for calculations in this model.

The rate of heat energy per unit width lost through convection from the upper surface of the fluid to the atmosphere is calculated as (Kinsky, 1973);

$$q_{convective} = (T_{avg} - T_{air})\, l_{sl}\, h \qquad [A7]$$

where $q_{convective}$ = rate of energy loss via convection (J/s m),
T_{avg} = average groundwater temperature in heat exchange regime 1 (K),
T_{air} = design temperature (K),
l_{sl} = length in heat regime 1 (m), and
h = convective heat transfer coefficient per unit width (J/[s m^2 K])

The convective heat transfer coefficient per unit width is calculated as (Kinsky, 1973);

$$h = N_u\ (k_t/l_{sl}) \qquad [A8]$$

where h = convective heat transfer coefficient per unit width (J/[s m^2 K]),
N_u = Nusselt number (dimensionless),
k_t = thermal conductivity, and
assumed constant for water at 0°C = 0.522 J/[m s K]
l_{sl} = length in heat regime 1(m)

The Nusselt number is calculated as (Kinsky, 1973);

$$\begin{array}{ll} Nu = 0.54\,[G_r\, P_r]^{1/4} & \text{for } G_r < 2.7 * 10^7 \\ Nu = 0.14\,[G_r\, P_r]^{1/3} & \text{for } G_r \geq 2.7 * 10^7 \end{array} \qquad [A9]$$

where N_u = Nusselt number (dimensionless),
G_r = Grashof number (dimensionless), and
P_r = Prandtl number (dimensionless)

The Prandtl number is calculated as (Kinsky, 1973);

$$P_r = \mu\ c_p / k_t \qquad [A10]$$

where P_r = Prandtl number (dimensionless),
μ = dynamic viscosity (kg/[m s]),
c_p = specific heat (J/[kg K]), and
k_t = thermal conductivity, for water at 0°C = 0.522 J/[m s K]

The Grashof number is calculated as (Kinsky, 1973);

$$G_r = \frac{g\left(\frac{1}{T_{air}}\right)\left(T_{avg} - T_{air}\right) l_{sl}^3\ \rho^2}{\mu^2} \qquad [A11]$$

where G_r = Grashof number (dimensionless),
g = gravitational acceleration of 9.81 m/s^2,
T_{avg} = average groundwater temperature in heat exchange regime 1 (K),
T_{air} = design temperature (K),
l_{sl} = length in heat regime 1(m)
ρ = density of groundwater (kg/m^3), and
μ = dynamic viscosity (kg/[m s]).

Substitute equations A11 and A10 into equation A9, equation A9 into equation A8, and equation A8 into A7. Then substitute equations A2, A4 and A7 into A1 to get:

$$\dot{M}\,\Delta H = \frac{k_t (T_{avg} - T_{air})\, l_{sl}}{0.05\left[\frac{0.085\,\dot{M}\,\mu}{g\,\rho^2 \sin\phi}\right]^{1/3}} + 0.54\left(T_{avg} - T_{air}\right) k_t \left[\frac{g\left(\frac{1}{T_{air}}\right)\left(T_{avg} - T_{air}\right) l_{sl}^3\ \rho^2\ c_p}{\mu\, k_t}\right]^{1/4} \qquad [A12a]$$

for $G_r < 2.7 * 10^7$, and

$$\dot{M}\Delta H = \frac{k_t(T_{avg} - T_{air})l_{sl}}{0.05\left[\frac{0.085\dot{M}\mu}{g\rho^2 \sin\phi}\right]^{1/3}} + 0.14(T_{avg} - T_{air})k_t\left[\frac{g\left(1/T_{air}\right)(T_{avg} - T_{air})l_{sl}^3 \rho^2 c_p}{\mu k_t}\right]^{1/3} \quad [A12b]$$

for $G_r \geq 2.7 * 10^7$

Equations [A12a] and [A12b] are complex, and it is not obvious that the equation gives a correct answer in terms of the units involved. Equation [A12b] is re-written below with the units only to demonstrate that the equation is internally consistent.

$$\frac{\cancel{kg}}{s\,m}\frac{J}{\cancel{kg}} = \frac{J\cancel{(K)}\cancel{m}}{\cancel{m}s\cancel{K}\left[\frac{\cancel{kg(kg)s^2m^3}\,m^3}{\cancel{sm(ms)mkg^2}}\right]^{1/3}} + \frac{\cancel{K}(J)}{(ms\cancel{K})}\left[\frac{\cancel{mK^{-1}Km^3(kg^2)J\{ms\}msK}}{\cancel{s^2(m^3)^2\,kgK\{kg\}J}}\right]^{1/3} \quad [A12b]$$

For a given groundwater outlet temperature (T_o), the values of ρ and μ will be constant. For a given mass flow rate per unit width ($\dot{M}$), the Grashof number can be calculated to determine which of equations [A12a] or [A12b] to use to calculate the last variable; the length for heat regime 1. A simple spreadsheet file was created to calculate the length for regime 1 over a range of groundwater outlet temperature and mass flow rate per unit width, either through trial and error or by using a built-in equation solving function such as Solver in Microsoft Excel.

Heat exchange regime 2: Freeze separation as the groundwater cools to air temperature

The length for heat exchange regime 2 was solved using an iterative method. As flowing groundwater cools below its freezing point temperature, ice crystals form and are removed from the flow. As the flow temperature decreases,

- the mass flow rate per unit width decreases,
- the water film thickness decreases,
- the flow velocity decreases,
- and concentration increases.

The sequence to calculate length for heat regime 2 in an iterative method is:

1. Knowing the design temperature (T_{air}), look up the maximum final salt concentration (i.e., for sodium chloride, see Table 4.5) measured in kg/L
2. Knowing the initial groundwater outlet concentration (C_o, in kg/L) and for a given initial mass flow rate per unit width ($\dot{M}_o$), calculate the rate that salt is added in the groundwater at the inlet, per unit width, as;

$$\dot{M}_{salt} = (\dot{M} / \rho)\, C_o \ \ (1\mathrm{L}/10^{-3}\ \mathrm{m}^3) \qquad [A13]$$

where: $\dot{M}_{salt}$ = mass rate that salt is added in the groundwater per unit width (kg_{salt}/s m),
$\dot{M}$ = mass groundwater flow rate per unit width (kg_{aq}/s m),
ρ = density of groundwater (kg_{aq}/m^3), and
C_o = initial salt concentration in groundwater (kg_{salt}/L)

3. Calculate the rate of water needed per unit width when the final concentration (C_f) is reached as;

$$\dot{M}_{brine} = \{\dot{M}_{salt}\, \rho / C_f\}\ (10^{-3}\ \mathrm{m}^3/\mathrm{L}) \qquad [A14]$$

where: $\dot{M}_{brine}$ = mass groundwater flow rate per unit width required for final concentration (kg_{aq}/s m),
$\dot{M}_{salt}$ = mass rate that salt is added in the groundwater per unit width (kg_{salt}/s m),
$\dot{M}$ = mass groundwater flow rate per unit width (kg_{aq}/s m),
ρ = density of groundwater (kg_{aq}/m^3), and
C_f = final salt concentration in groundwater (kg_{salt}/L)

4. Calculate the mass rate of water removed ($\dot{M}_r$) as ice in order to reach final concentration (C_f) as;

$$\dot{M}_r = \dot{M}_o - \dot{M}_{brine} \qquad [A15]$$

where: $\dot{M}_r$ = mass groundwater flow rate removed by ice formation per unit width (kg_{aq}/s m),
$\dot{M}_o$ = initial mass groundwater flow rate per unit width (kg_{aq}/s m), and
$\dot{M}_{brine}$ = mass groundwater flow rate per unit width required for final concentration (kg_{aq}/s m).

5. Calculate the total heat energy to be removed as latent heat of fusion by ice formation as;

$$q_{tot} = \dot{M}_r\, L \qquad [A16]$$

where: q_{tot} = total rate of heat energy released by ice formation per unit width (J/s m),
$\dot{M}_r$ = mass groundwater flow rate removed by ice formation per unit width (kg_{aq}/s m), and
L = latent heat of fusion of ice as 0.335×10^6 J/kg_{aq}.

6. Knowing $C_{(i-1)}$ (initially C_o), $\dot{M}_{(i-1)}$ (initially $\dot{M}_o$), and $T_{(i-1)}$ (initially the freezing point of the liquid) and using a constant iteration value of the length for heat regime 2 ($l_{s\ i}$) of 0.1 m, begin the iterative calculations with the temperature difference between flowing groundwater and air (design) temperature as;

$$\Delta T_i = T_{(i-1)} - T_{air} \qquad [A17]$$

7. Calculate the flowing groundwater film thickness (B_i) using equation [A6]

8. Estimate the boundary layer thickness (b_i) of the flowing groundwater as 5% of B_i

9. Calculate the Grashof number ($G_{r\,i}$) using equation [A11]

10. Calculate the Nusselt number ($N_{u\,i}$) using equation [A9]

11. Calculate the convective heat transfer coefficient (h_i) using equation [A8]

12. Calculate the conductive heat loss rate per unit width using a variant of equation [A4];

$$q_{conductive\,i} = k_t\,\Delta T_i\,l_{s\,i} / b_i \qquad [A4b]$$

where: $q_{conduction\,i}$ = rate of energy loss via conduction (J/s m),
k_t = thermal conductivity (J/[m s K]),
assumed constant for water near 0 °C as 0.522 J/[m s K]
ΔT_i = temperature difference between groundwater and air (K),
$l_{s\,i}$ = iterative length in heat regime 2 (0.1 m), and
b_i = thickness of boundary layer (m)

13. Calculate the convective heat loss rate per unit width using a variant of equation [A7];

$$q_{convective\,i} = h_i\,l_{s\,i}\,\Delta T_i \qquad [A7b]$$

where $q_{convective\,i}$ = rate of energy loss via convection (J/s m),
h_i = convective heat transfer coefficient per unit width (J/[s m^2 K]),
$l_{s\,i}$ = iterative length in heat regime 2 (0.1 m), and
ΔT_i = temperature difference between groundwater and air (K).

14. Calculate the fraction of mass flow removed as ice in this iteration as;

$$\Delta \dot{M}_i = \frac{\left(q_{conductivei} + q_{convectivei}\right)}{q_{tot}} * \left(\dot{M}_o - \dot{M}_{brine}\right) \qquad [A18]$$

where $\Delta \dot{M}_i$ = Fraction of mass flow removed as ice in this iteration ($\mathrm{kg_{aq}}$/s m)
$q_{conduction\,i}$ = rate of energy loss via conduction (J/s m),
$q_{convective\,i}$ = rate of energy loss via convection (J/s m),
q_{tot} = total rate of heat energy released by ice formation per unit width (J/s m),

$\dot{M}_o$ = initial mass flow rate per unit width (kg_{aq}/s m), and
$\dot{M}_{brine}$ = mass flow rate per unit width required at final concentration (kg_{aq}/s m).

15. Calculate the new groundwater temperature (T_i) for this iteration as;

$$T_i = T_{(i-1)} - \left[\left(\frac{q_{convective\,i} + q_{conductive\,i}}{q_{tot}}\right)\Delta T_i\right] \quad [A19]$$

where T_i = Groundwater temperature for this iteration (K),
$T_{(i-1)}$ = Groundwater temperature from previous iteration (K),
$q_{conduction\,i}$ = rate of energy loss via conduction (J/s m),
$q_{convective\,i}$ = rate of energy loss via convection (J/s m),
q_{tot} = total rate of heat energy released by ice formation per unit width (J/s m), and
ΔT_i = temperature difference between groundwater and air (K) for this iteration.

16. Calculate the mass flow rate per unit width for this iteration as;

$$\dot{M}_i = \dot{M}_{(i-1)} - \Delta\dot{M}_i \quad [A20]$$

17. Calculate the concentration of the groundwater for this iteration as;

$$C_i = (\dot{M}_{salt}\rho / \dot{M}_i)(10^{-3}\ m^3/L) \quad [A21]$$

18. Because the iterative calculations use constantly diminishing output from the previous iteration as input to the next iteration, the iterations were completed when the output of concentration, mass flow rate per unit width or groundwater temperature were close to the final values. When the following conditions were true, the iteration was completed:

- $\dot{M}_i > \dot{M}_{brine}$,
- $C_i > (C_f - 0.002)$, or
- $T_i > (T_{air} - 0.025)$

Once the iterative calculations are completed, multiply the number of iterations by 0.1 to determine the length for heat regime 2 (l_{sII}). The total significant length is the sum of l_{sI} and l_{sII}.

Otherwise, the values for C_i, $\dot{M}_i$, and T_i are carried forward to step 6 for the next iteration as $C_{(i-1)}$, $\dot{M}_{(i-1)}$, and $T_{(i-1)}$ respectively, and the next iteration follows the same sequence of calculations.

A spreadsheet was created to simplify the calculation of lengths for heat regime 2 (l_{sII}) for various mass flow rates per unit width, initial concentrations and air temperatures using the process described above.

Appendix 2: Groundwater Well Tests, 17 September 2000

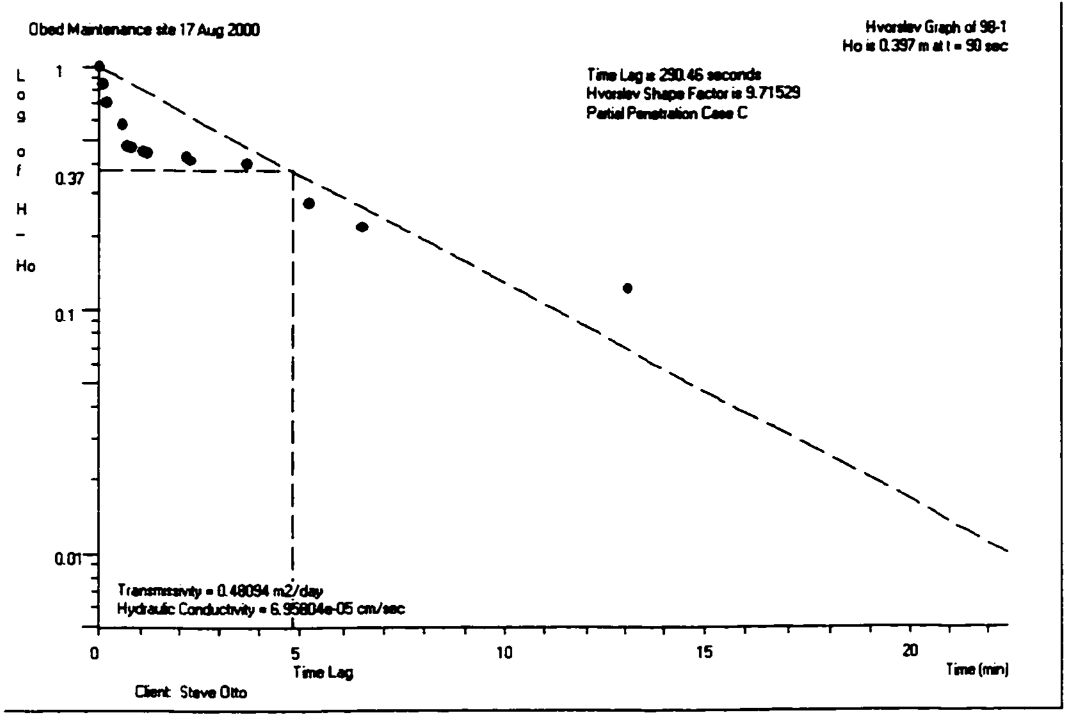


Figure A2.1 Well test 17 Aug. 2000, well 98-1

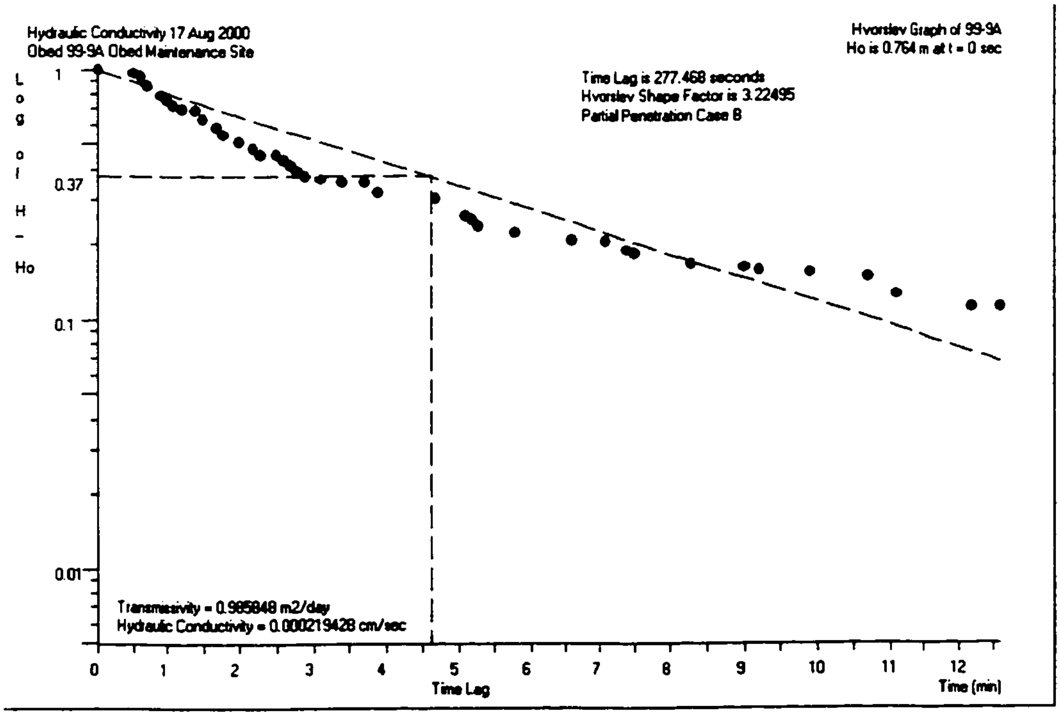


Figure A2.2 Well test 17 Aug 2000, well 99-9A

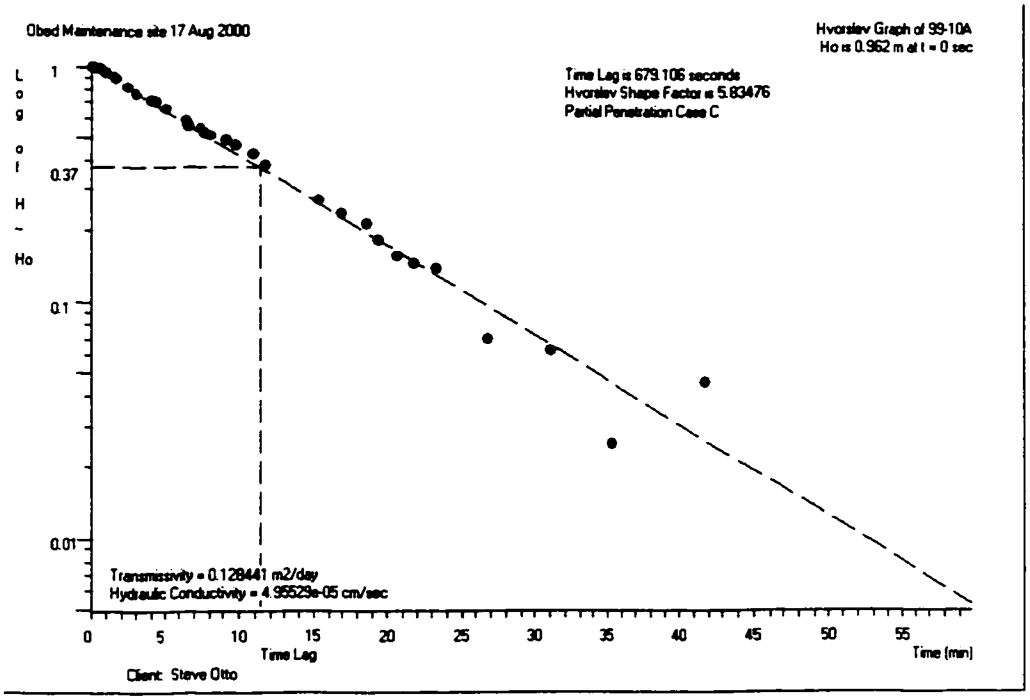


Figure A2.3 Well test 17 Aug. 2000, well 99-10A

Appendix 3: Geophysical Testing at Obed Maintenance Site

The grid used for geophysical testing using a EM 31 conductivity meter 17 August, 2001 is shown in Figure A3, below:

Grid spacing approximately 10 meters per side

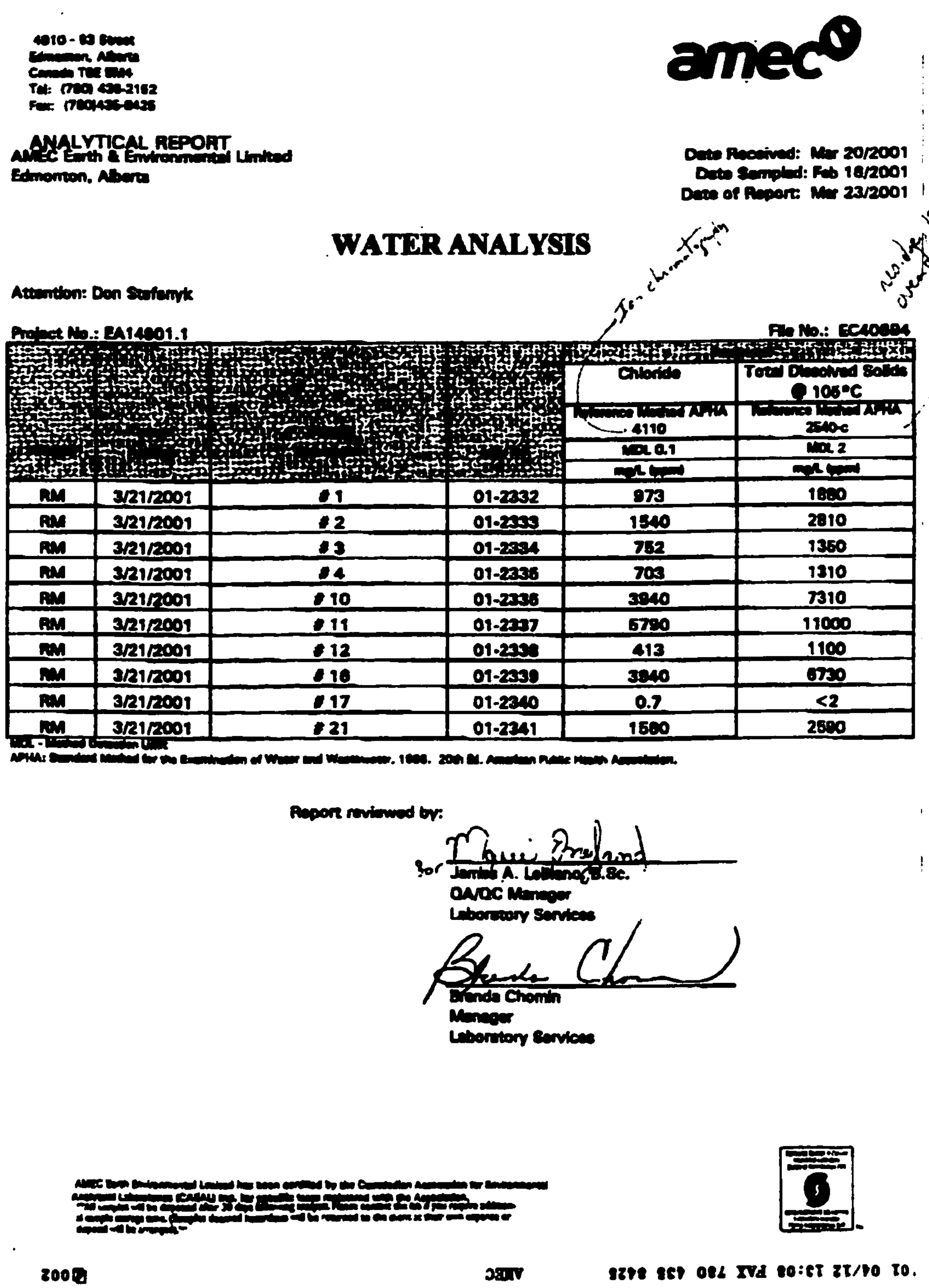
Figure A3: EM survey at Obed Maintenance site, August 2001

Table A3 EM 31 Readings at Obed Maintenance site, August 2001

	Column 0	Column 10	Column 20	Column 30	Column 40	Column 50	Column 60	Column 70
Row 0	44	37	40	56	39	32	33	31
Row 10	37	42	52	58	36	30	29	28
Row 20	37	50	66	50	74	40	24	28
Row 30	36	46	100	65	60	29	24	28
Row 40	35	44	38	50	33	32	26	28
Row 50	37	42	49	88	38	28	32	36
Row 60	34	42	48	94	42	38	35	64
Row 70	46	48	54	44	47	36	32	61
Row 80	48	50	54	42	44	38	29	28

(EM 31 readings in 10 x mS/cm)

Appendix 4: Laboratory Test Results



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Fax: (780)435-8425

ANALYTICAL REPORT
AMEC Earth & Environmental Limited
Edmonton, Alberta

Date Received: Mar 20/2001
Date Sampled: Feb 16/2001
Date of Report: Mar 23/2001

WATER ANALYSIS

Ion chromatography

no drying 180°C
oven dry

Attention: Don Stefanyk

Project No.: EA14801.1

File No.: EC40884

[illegible]	[illegible]	[illegible]	[illegible]	Chloride	Total Dissolved Solids @ 105°C
				Reference Method APHA 4110	Reference Method APHA 2540-c
				MDL 0.1	MDL 2
				mg/L (ppm)	mg/L (ppm)
RM	3/21/2001	# 1	01-2332	973	1880
RM	3/21/2001	# 2	01-2333	1540	2810
RM	3/21/2001	# 3	01-2334	752	1350
RM	3/21/2001	# 4	01-2335	703	1310
RM	3/21/2001	# 10	01-2336	3940	7310
RM	3/21/2001	# 11	01-2337	5790	11000
RM	3/21/2001	# 12	01-2338	413	1100
RM	3/21/2001	# 16	01-2339	3840	6730
RM	3/21/2001	# 17	01-2340	0.7	<2
RM	3/21/2001	# 21	01-2341	1580	2590

MDL - Method Detection Limit
APHA: Standard Method for the Examination of Water and Wastewater, 1998. 20th Ed. American Public Health Association.

Report reviewed by:

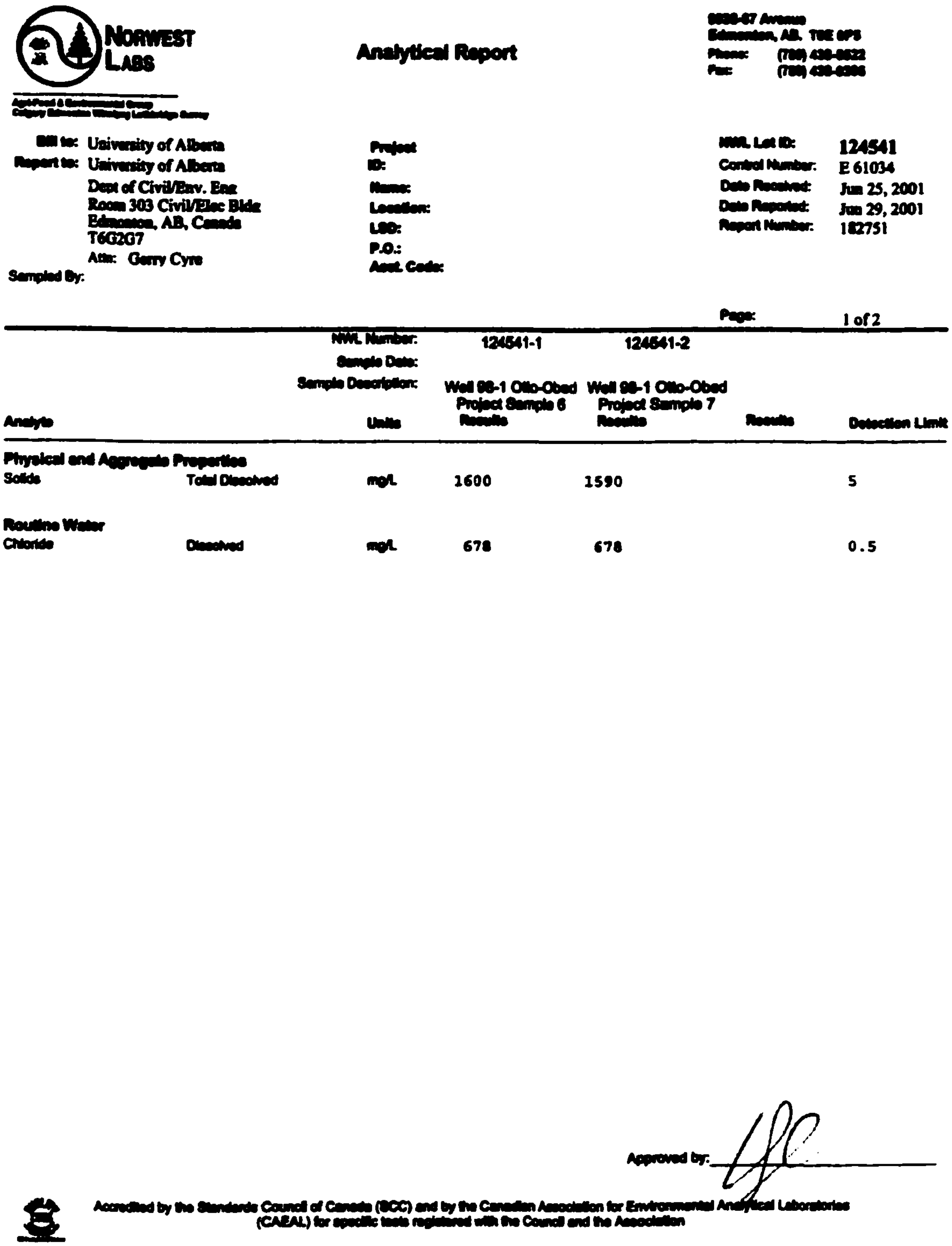
for James A. LeBlanc, B.Sc.
QA/QC Manager
Laboratory Services

Brenda Chomin
Manager
Laboratory Services

AMEC Earth & Environmental Limited has been certified by the Canadian Association for Environmental Analytical Laboratories (CAEAL) Inc. for specific tests registered with the Association.
"All samples will be disposed after 30 days following analysis. Please contact the lab if you require additional sample storage time. Samples deemed hazardous will be returned to the client at their own expense or disposal will be arranged."

01 04/12 13:08 FAX 780 438 8428 AMEC 002

Figure A4.1 AMEC laboratory test results, 23 March 2001



NORWEST LABS

Analytical Report

[illegible]-67 Avenue
Edmonton, AB. T6E [illegible]
Phone: (780) 438-[illegible]
Fax: (780) 438-[illegible]

Bill to:	University of Alberta	**Project**		**NWL Lot ID:**	**124541**
Report to:	University of Alberta	**ID:**		**Control Number:**	E 61034
	Dept of Civil/Env. Eng	**Name:**		**Date Received:**	Jun 25, 2001
	Room 303 Civil/Elec Bldg	**Location:**		**Date Reported:**	Jun 29, 2001
	Edmonton, AB, Canada T6G2G7	**LSD:**		**Report Number:**	182751
	Attn: Gerry Cyre	**P.O.:**			
Sampled By:		**Acct. Code:**			
				Page:	1 of 2

		NWL Number:	124541-1	124541-2		
		Sample Date:				
		Sample Description:	Well 98-1 Otto-Obed Project Sample 6	Well 98-1 Otto-Obed Project Sample 7		
Analyte		**Units**	**Results**	**Results**	**Results**	**Detection Limit**
Physical and Aggregate Properties						
Solids	Total Dissolved	mg/L	1600	1590		5
Routine Water						
Chloride	Dissolved	mg/L	678	678		0.5

Approved by:

Accredited by the Standards Council of Canada (SCC) and by the Canadian Association for Environmental Analytical Laboratories (CAEAL) for specific tests registered with the Council and the Association

Figure A4.2 Norwest Labs laboratory test results, 29 June 2001

Appendix 5: Photos

Photo A5.1: Berm construction, 6 Feb. 2001

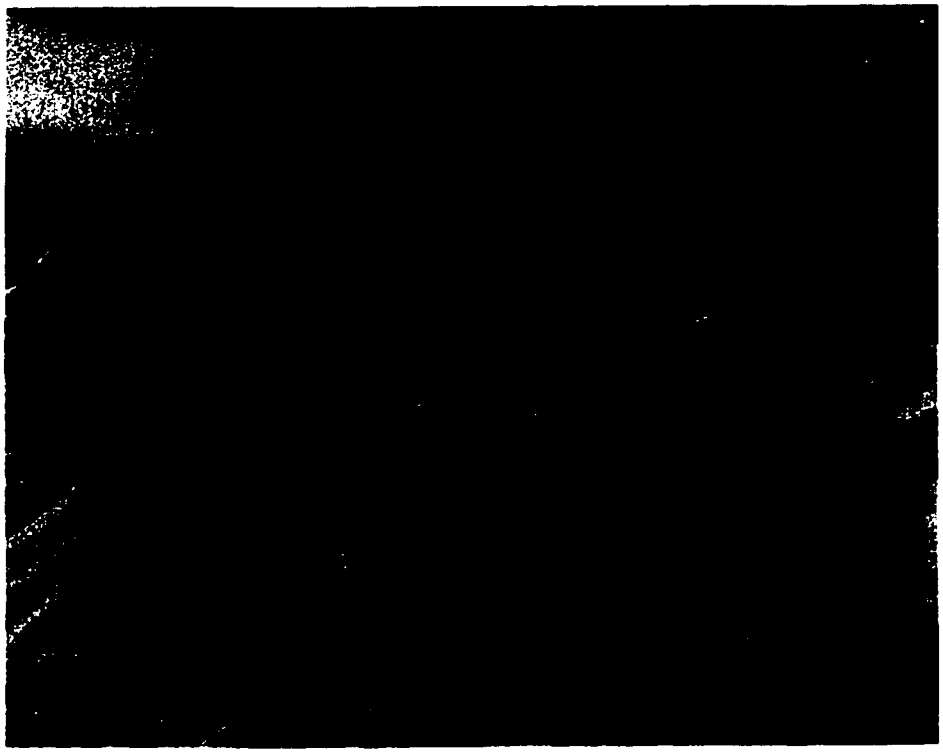


Photo A5.2: Preparing to install the geomembrane, 12 Feb. 2001

Photo A5.3: Geomembrane laid out, 12 Feb. 2001

Photo A5.4: Laying out the tubing. 12 Feb. 2001

Photo A5.5: Retaining ponds at start of extraction, 12 Feb. 2001

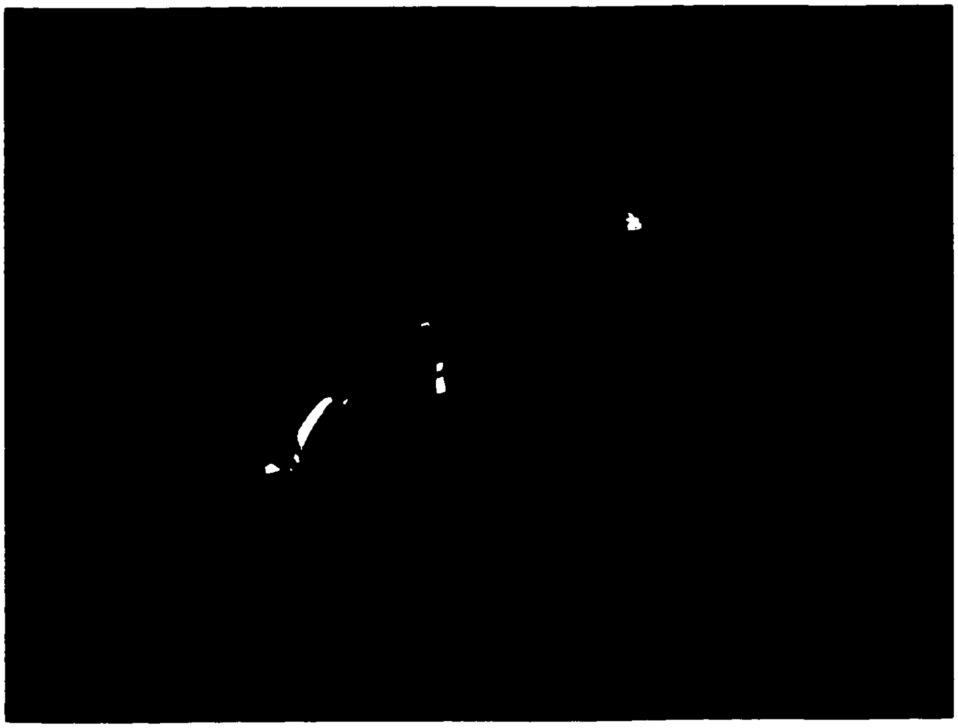


Photo A5.6: Sampling from well 98-1, 12 Feb. 2001

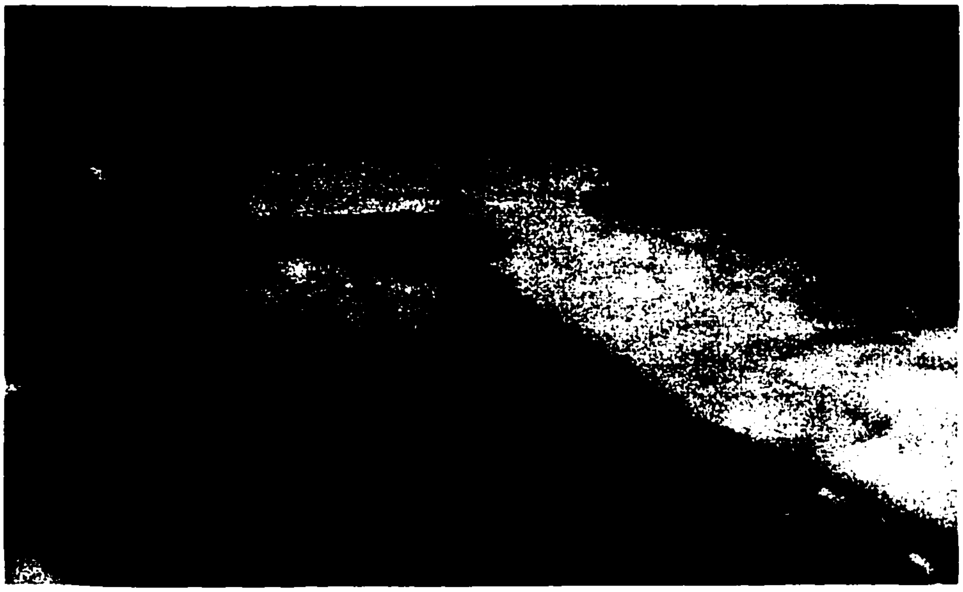


Photo A5.7: Brine separation 13 Feb. 2001, well 98-1

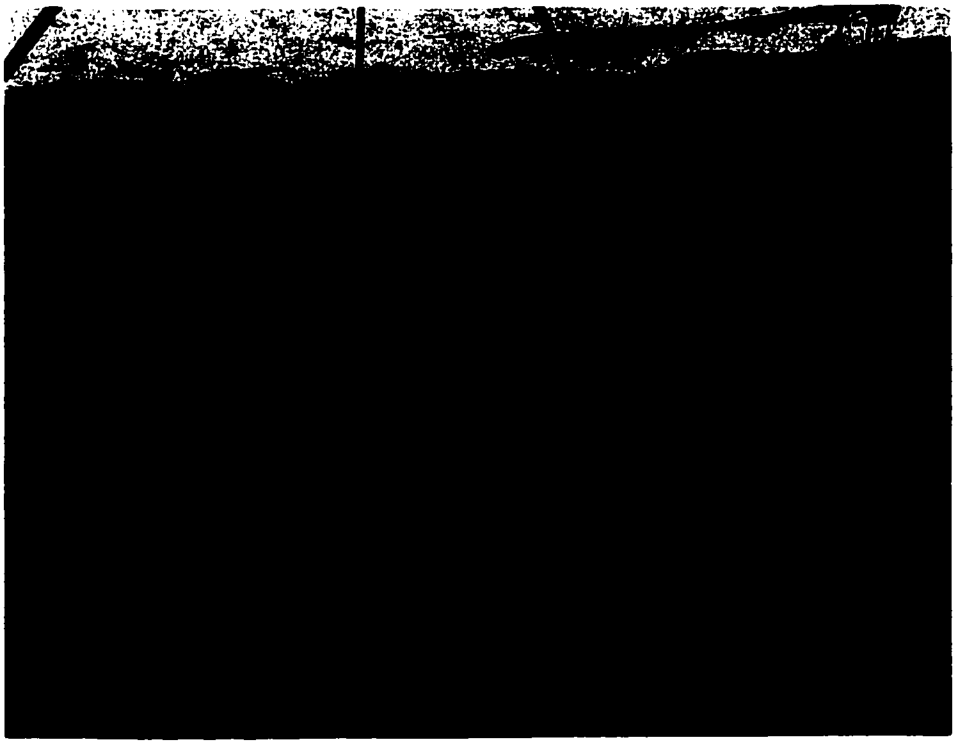


Photo A5.8: Brine Separation 13 Feb. 2001, well 99-9A

Appendix 6: Significant length plots used to create Figure 4.8

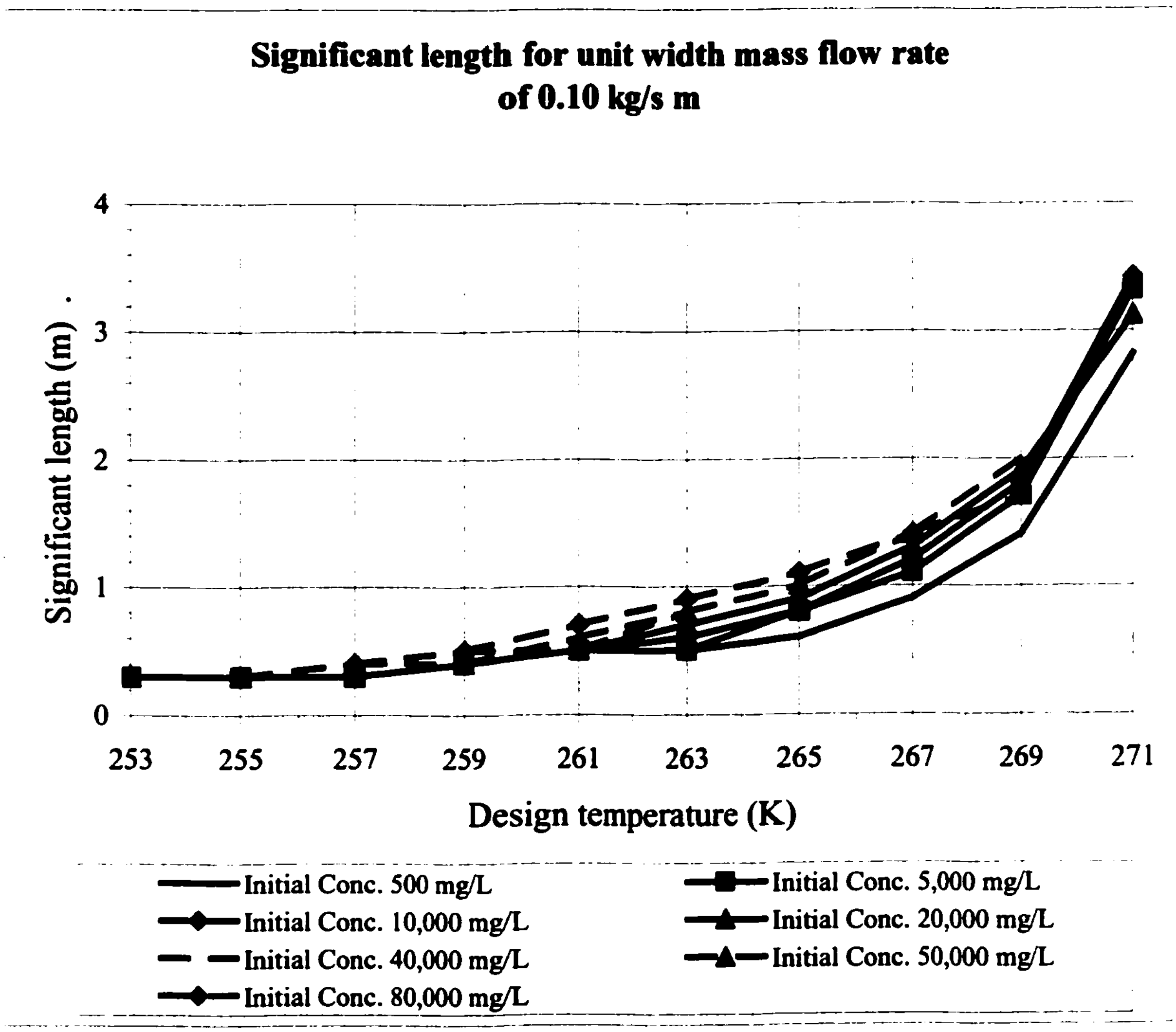


Figure A6.1 Significant length for a mass flow rate per unit width of 0.10 kg/s m

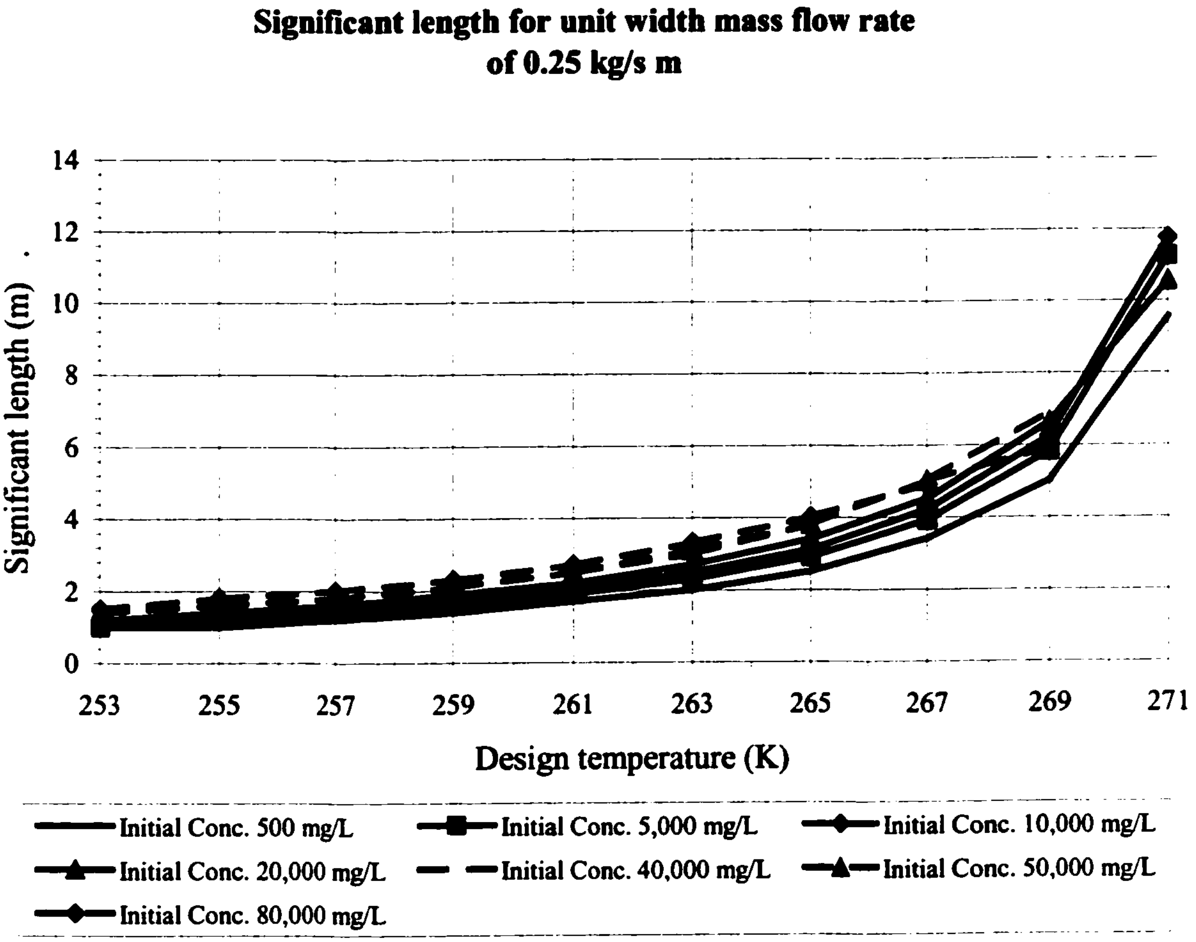


Figure A6.2 Significant length for a mass flow rate per unit width of 0.25 kg/s m

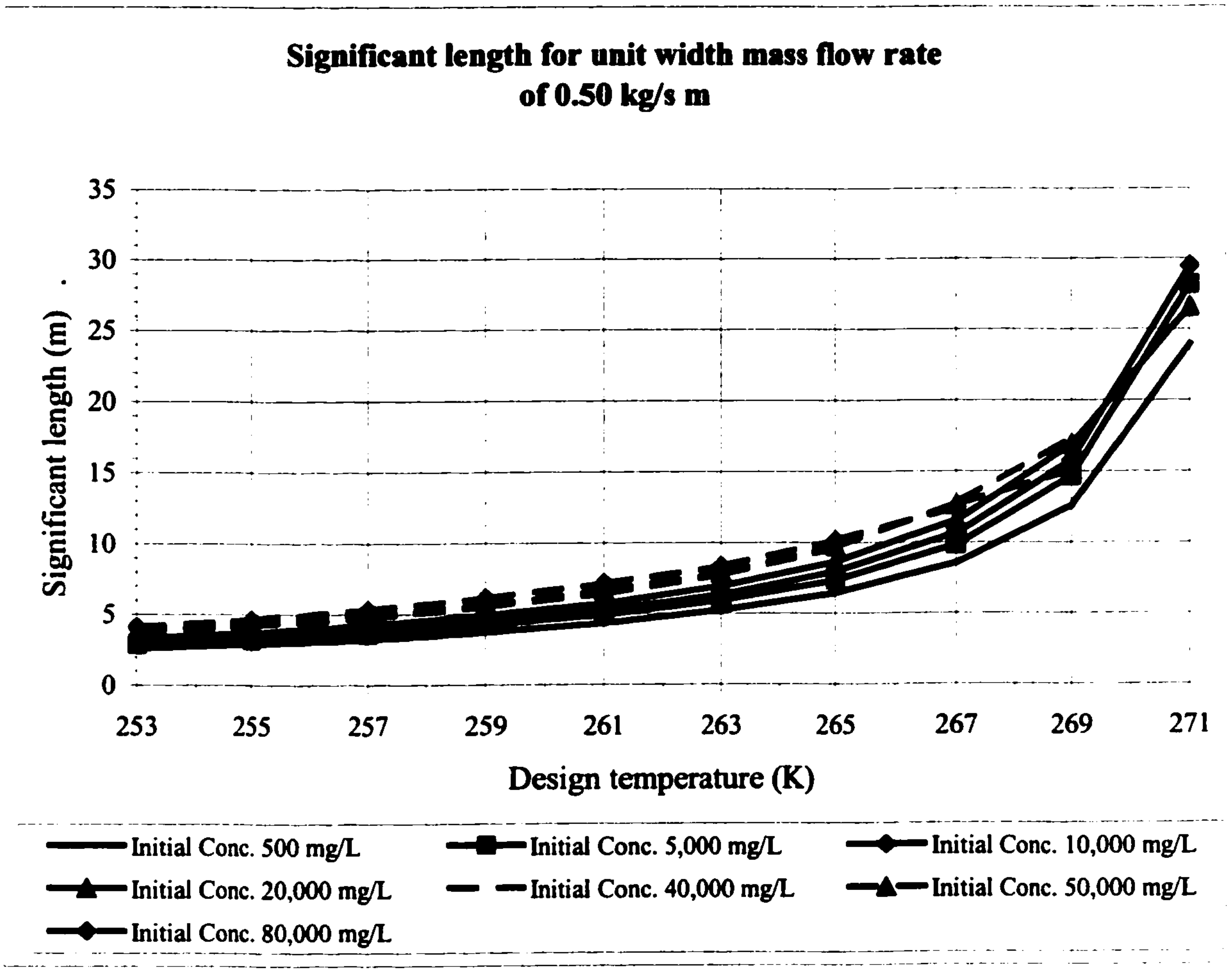


Figure A6.3 Significant length for mass flow rate per unit width of 0.50 kg/s m

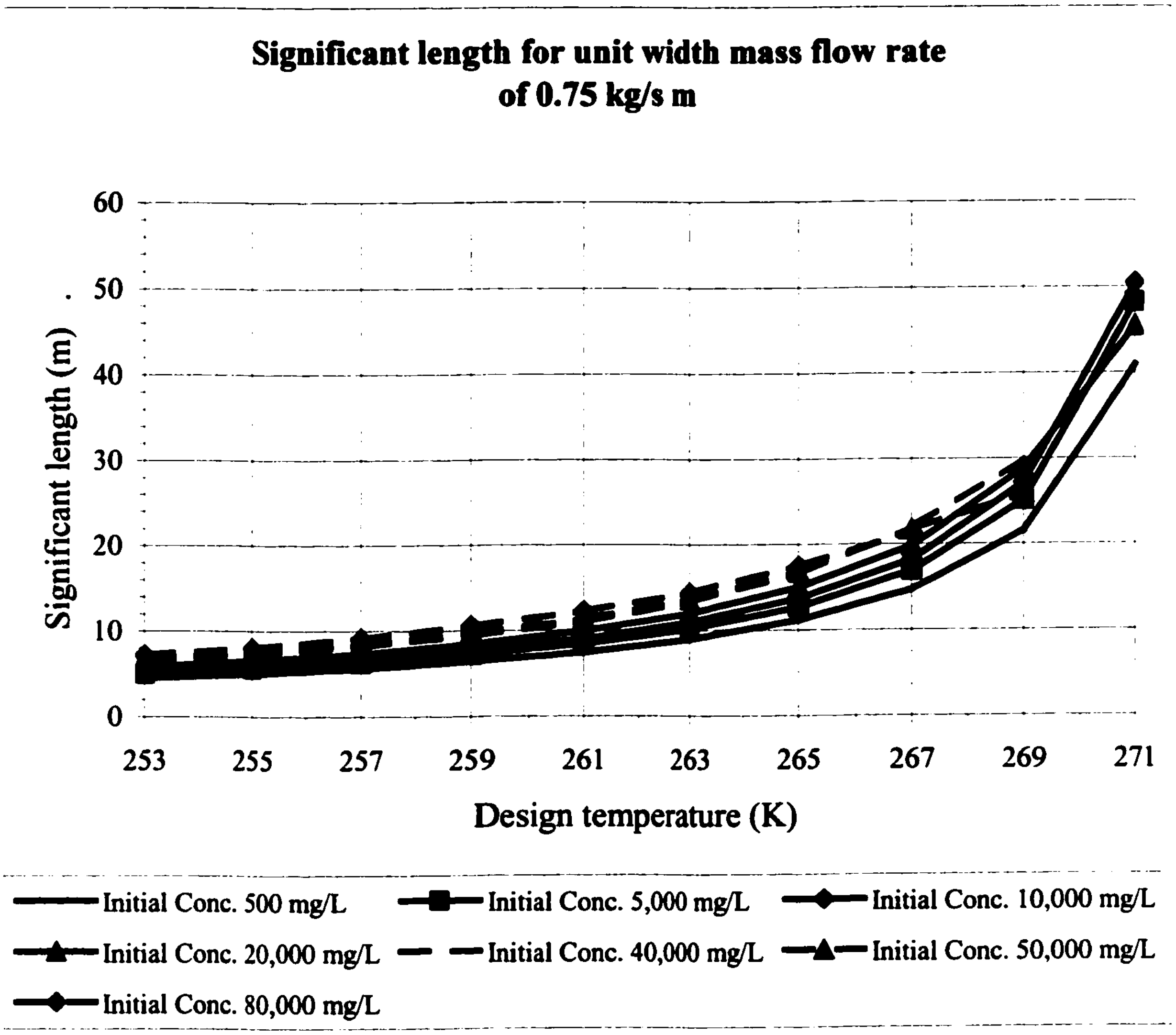


Figure A6.4 Significant length for a mass flow rate per unit width of 0.75 kg/s m

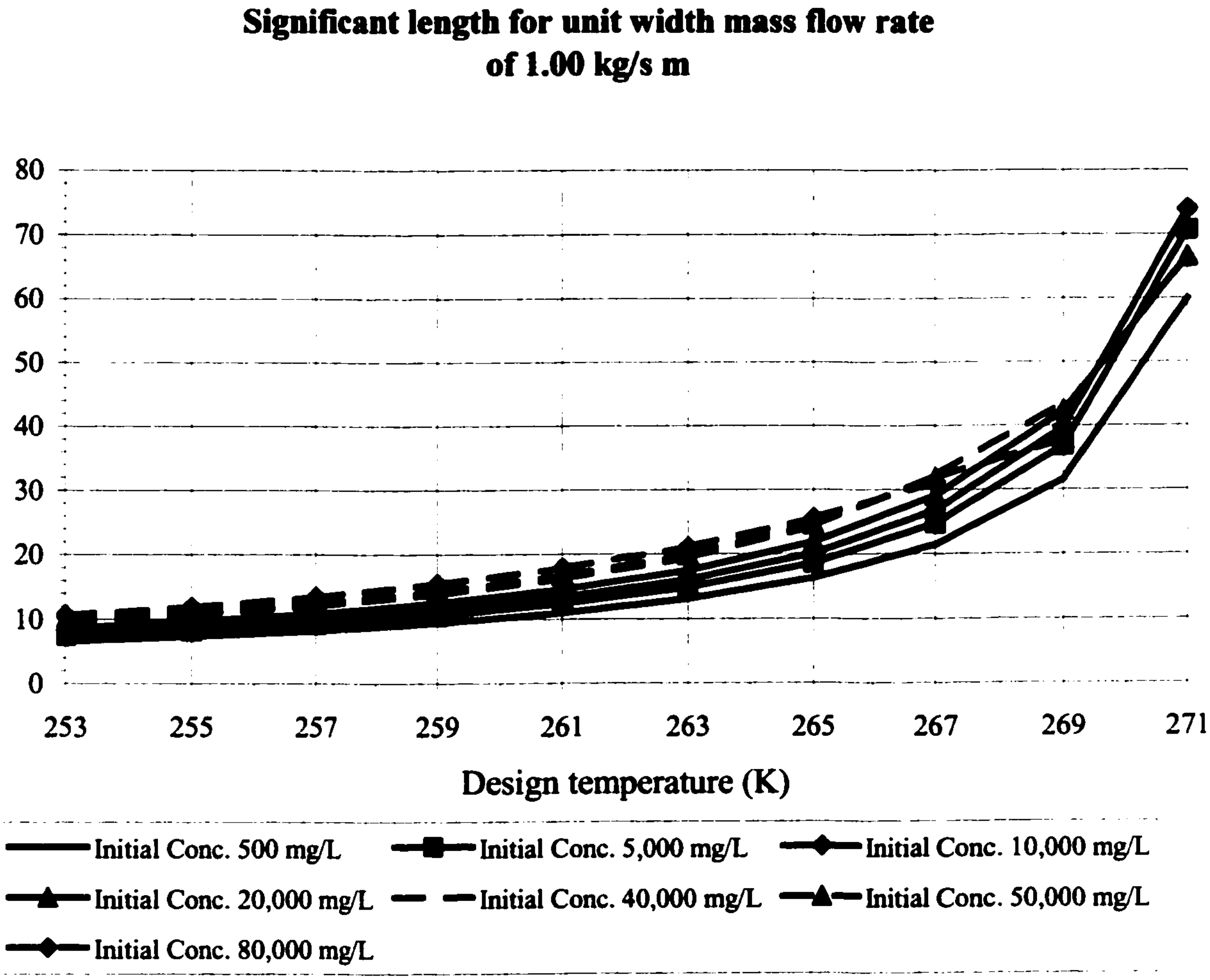


Figure A6.5 Significant length for a mass flow rate per unit width of 1.00 kg/s m

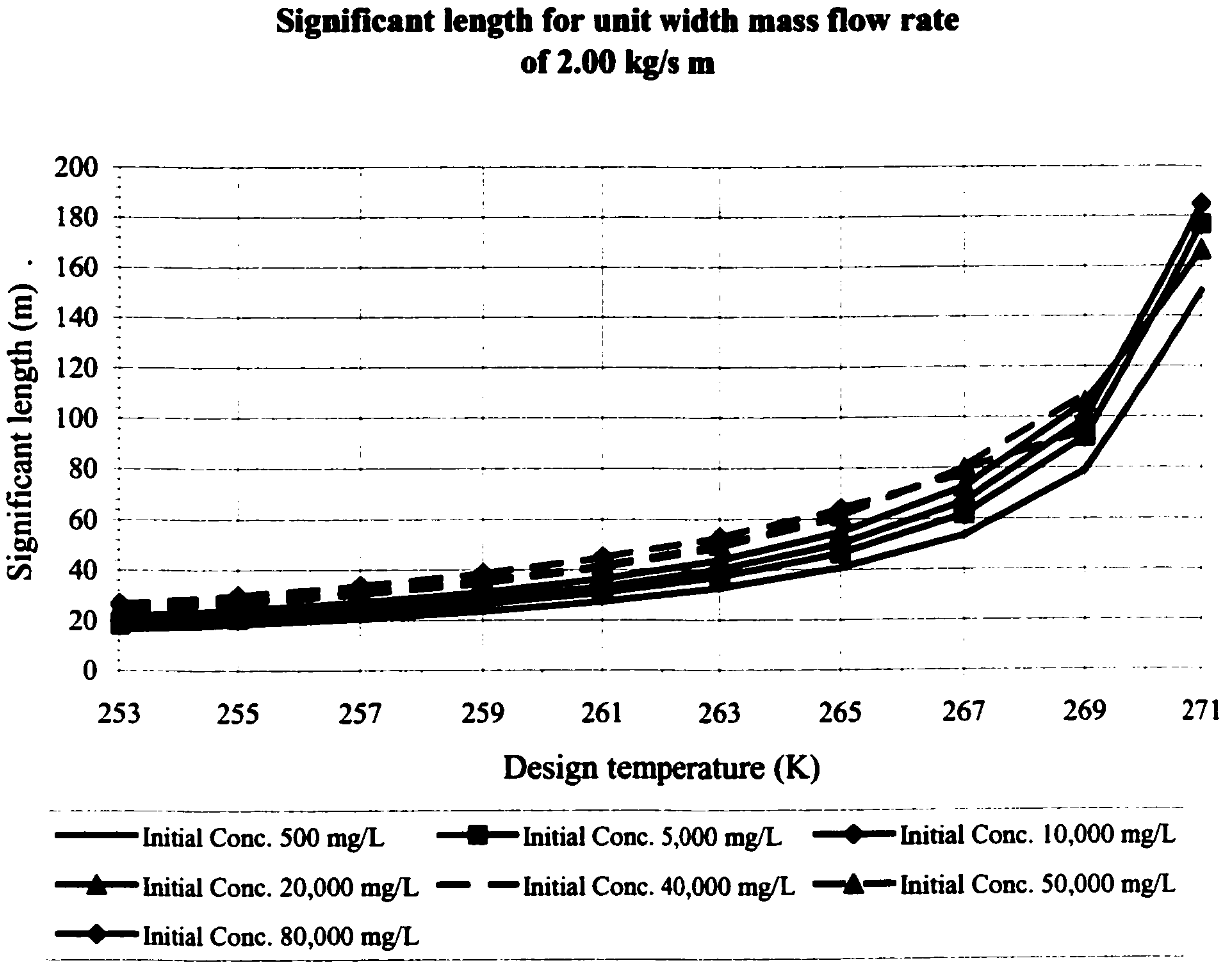


Figure A6.6 Significant length for a mass flow rate per unit width of 2.00 kg/s m

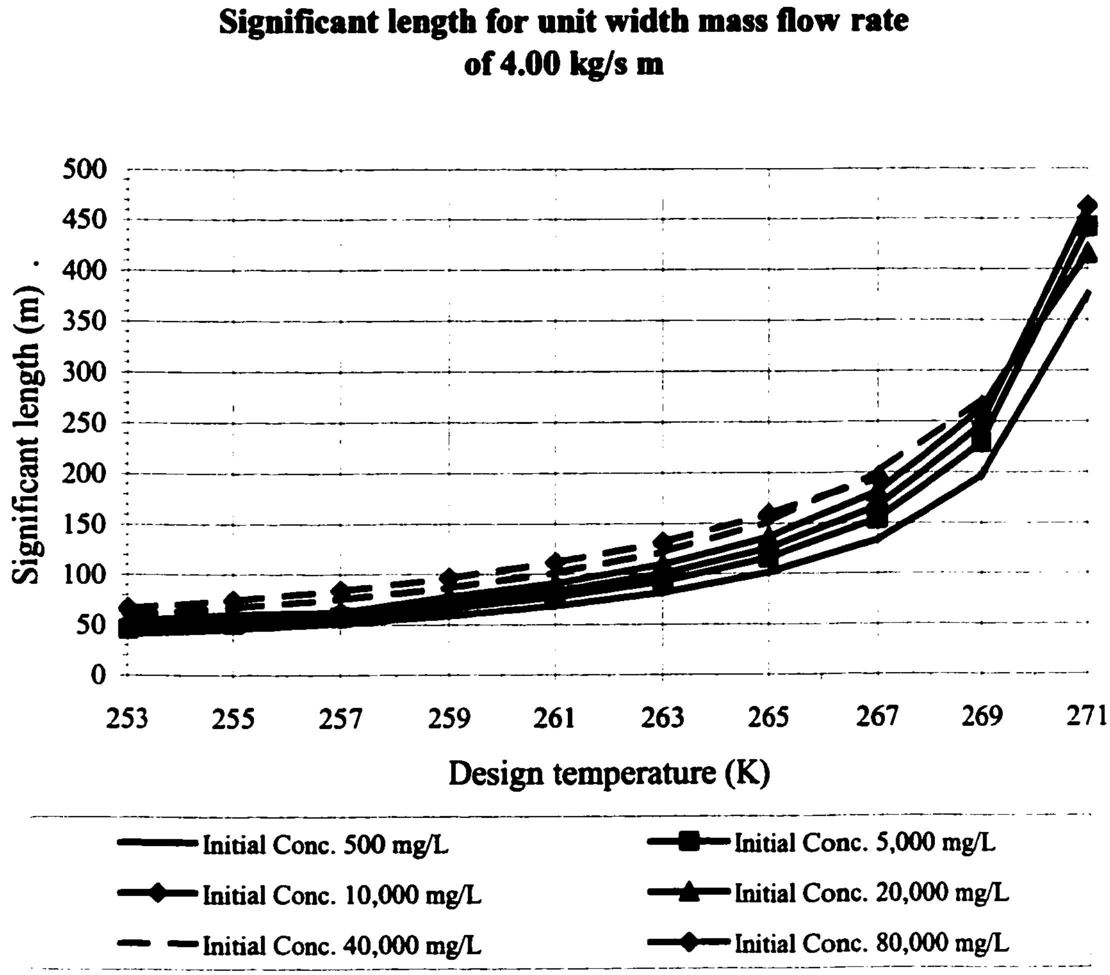


Figure A6.7 Significant length for a mass flow rate per unit width of 4.00 kg/s m