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PRACTICAL ASSESSMENT OF BRINE MIGRATION FROM A POTASH TAILINGS MANAGEMENT AREA

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ABSTRACT

Numerical modelling is a powerful tool that has become common in engineering use in recent years. With advancements in hardware and software, complex models can be developed to simulate numerous problems related to the mining industry, including seepage flows, solute transport, and deformations. Numerical modelling is often required for the planning, operation and decommissioning of minesites. However, even though the models used will provide solutions with high precision, it is important to recognize that the systems being modelled are probabilistic. The inputs to the model can not be established with certainty. This uncertainty in the inputs generates uncertainty in the model outputs, regardless of how sophisticated the numerical model is. In many cases, a probabilistic treatment of the problem, using a less sophisticated numerical model, yields cost effective, timely and insightful results.

As an example, a probabilistic methodology was used to quantify the potential for off-site brine migration from the tailings management facility of a potash mine. Conventional practice would have utilized a deterministic analysis with a (complex) seepage/solute transport model; however, after investigating the problem further, a simple (1-dimensional) solute transport model was adopted and implemented within a discrete probabilistic simulation framework. This methodology permitted the estimation of the potential for off-site brine migration.

The methodology is outlined in the paper within the context of a specific application conducted at the Agrium Inc. potash mine located near Vanscoy, Saskatchewan. It is simple and applicable to many problems requiring numerical simulation in mining and mine decommissioning.

1.0 INTRODUCTION

Numerical modelling is a powerful tool that has become common in engineering use in recent years. With advancements in hardware and software, complex models can be developed to simulate numerous problems related to the mining industry, including seepage flows, solute transport and deformations. Numerical modelling is often required for the planning, operation and decommissioning of minesites. However, even though the models used will provide solutions with high precision, it is important to recognize that the physical systems being modelled are probabilistic. The values of the model inputs can not be established with certainty. This uncertainty in the inputs generates uncertainty in the model outputs, regardless of how sophisticated the numerical model is. In many cases, a probabilistic treatment of the problem, using a less sophisticated model, yields cost effective, timely and insightful results.

This paper presents a summary of a case history of the use of discrete probabilistic simulation to investigate the potential for off-site brine migration from the Agrium Inc. (formerly Cominco Fertilizers) potash mine near Vanscoy, Saskatchewan. The study was conducted by AGRA Earth & Environmental Limited (AEE, formerly HBT AGRA Limited) in 1992-1993.

2.0 BACKGROUND

The Tailings Management Facility (TMF) at the Agrium Inc. Potash Mine near Vanscoy, Saskatchewan occupies approximately 370 ha in Twp. 35, Rge. 8, W3M. The layout of the TMF is shown on Figure 1. The current operation of the TMF involves hydraulically discharging the combined salt tailings and insols ("slimes") waste streams from the mill on top of the salt pile and successively decanting the fluid through a series of ponds, polishing the brine effluent to obtain a clarified brine solution which is collected in the North Brine Pond.

The TMF is located in a shallow, local, northwest trending valley. The trough of the valley is generally oriented along the longitudinal axis of the TMF with the ground surface sloping towards the TMF on the west, south and east sides. The ground slopes away from the TMF on the north side of the TMF towards Rice Lake. The surficial soils in the area under consideration consist of an interbedded sand and silty sand unit which coarsens upward. The distribution of sand beds within this unit is chaotic and unpredictable, although individual sand beds may have considerable longitudinal continuity (Eyles et al, 1984). This surficial soil unit is underlain by a silty clay and clay unit which acts as an aquitard.

The purpose of this study was to examine the potential for off-site brine migration from the Northeast portion of Agrium's TMF towards NE22-35-8-W3M. The location of interest is shown as Section A-A on Figure 1. This location represents the shortest seepage path for off-site brine migration in the area under consideration. Brine migration from the TMF is known to be occurring in this area and is currently being monitored using a series of monitor wells and surface electromagnetic (EM) surveys. The scope of this study included a geotechnical investigation consisting of seventeen test holes and piezometers, field and laboratory hydraulic conductivity testing and engineering analysis.

In conducting this study, AEE intentionally imposed several limitations on the field program and on the subsequent engineering analysis in order to focus the study on the relevant issues and to facilitate the completion of the project within time and budgetary constraints. The scope of this study was defined as follows:

- The study area was defined as Section 15 and the northern half of Section 22 - Twp.35, Rge.8, W3M.

- The study was conducted for time frames of 25, 50 and 75 years assuming T=0 on January, 1, 1993.

- The progression of the brine front away from the TMF was modelled assuming its initial location was as defined by the EM survey work completed by the Saskatchewan Research Council (Maathuis, Jaworski and Zlipko, (1993)).

- The estimate of the likely extent of brine migration assumed that the operation of the TMF, and the corresponding flow regime around the TMF, remained essentially consistent with that established in December 1992 (i.e., steady state flow conditions).

- It was assumed that the pre-mine development flow regime would be re-established after the mine was decommissioned. This would result in groundwater flow back toward the TMF, reducing further brine migration toward the northeast.

- The development of finite difference or finite element computer models were considered to be "out of scope" for this study.

- Density dependent flow was modelled implicitly rather than explicitly.

- Discrete probabilistic simulation was used to quantify the uncertainty associated with the soil parameters and flow characteristics.

The level of effort required to develop a regional finite difference or finite element computer model capable of explicitly modelling density dependent flow would be far in excess of the budget allocated to this study. AEE specifically selected a probabilistic analysis framework to quantify shortcomings in the analysis resulting from either the simplistic nature of the solute transport model or the uncertainty associated with the soil parameter and flow characteristic estimates. If this preliminary assessment indicated a significant potential for off-site brine migration, a more complex analysis would have been implemented. Staging the analysis in this fashion was considered to be an efficient allocation of resources.

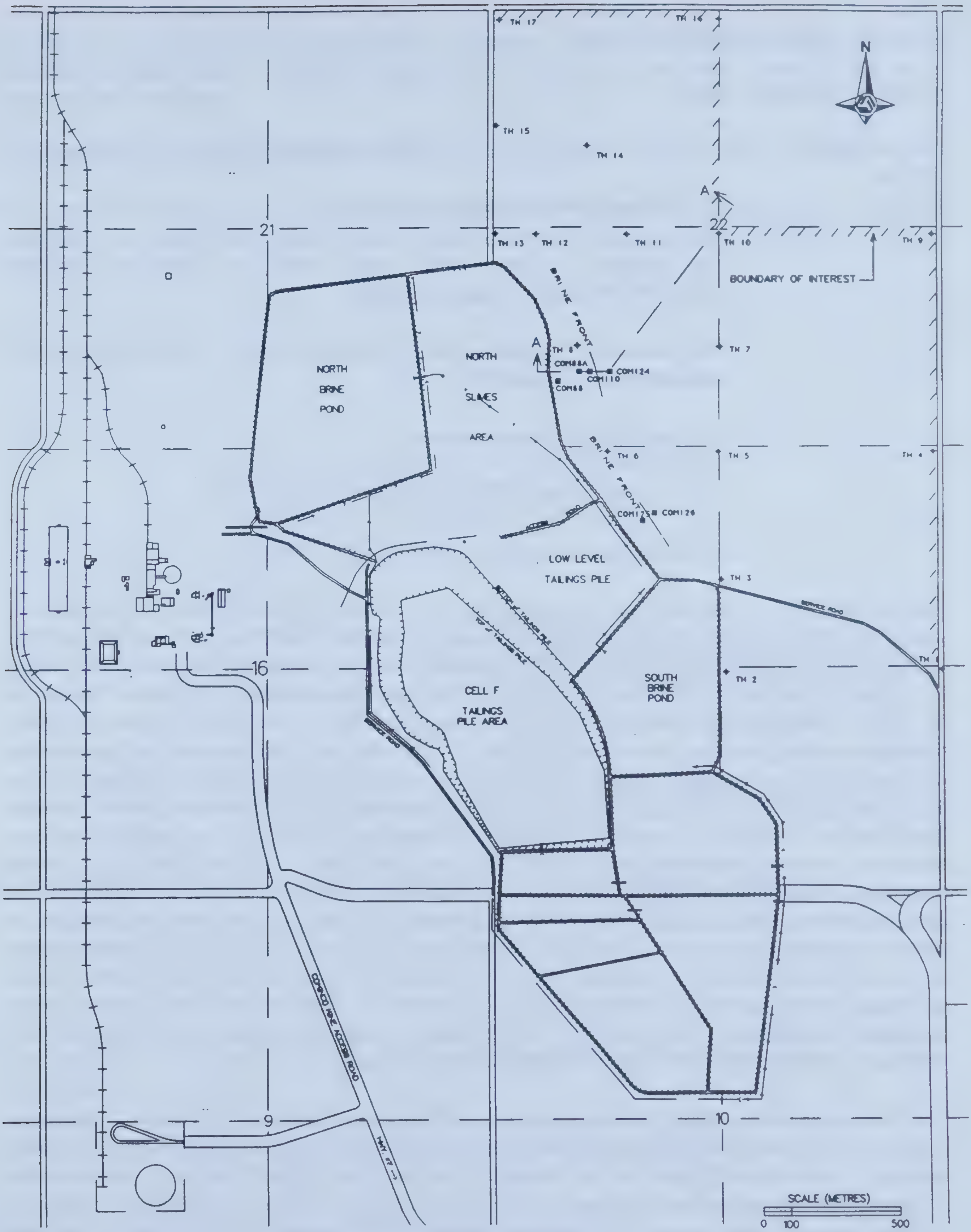

Figure 1 Site Plan

3.0 ANALYSIS METHODOLOGY

3.1 Solute Migration Model

The assumptions made for the analysis of the rate of brine migration from the TMF were as follows:

- The flow was one-dimensional (horizontal).
- The advance of the brine front could be described by the Advection-Dispersion Equation (ADE).
- The solute of concern (salt) was non-reactive, non-decaying, and conservative (no retardation).
- Only saturated flow was considered.
- The flow system was uniform and at steady state.
- The soils were homogeneous and isotropic

The assumption of one-dimensional flow has a slight error associated with it due to the existence of density dependant flow; however, as discussed above, the explicit modelling of density driven flow was beyond the scope of this project. Density dependent flow was implicitly modelled by adjusting the gradient in an attempt to simulate the higher driving head associated with the brine. The use of the ADE to calculate the movement of the brine front enabled the use of closed-form analytical solutions, resulting in rapid, yet accurate solutions. As a solute, salt is non-decaying and is generally non-reactive and non-retarded. However, this assumption neglects the possibility that precipitation of salt may occur. The assumption of saturated flow is reasonable, given that the aquifer in question is surficial and unconfined. As well, determination of unsaturated hydraulic conductivity functions and solute transport parameters was beyond the scope of this study. The assumption of a steady state flow system is a reasonable approximation given the scope of this study. It was recognized that the materials in the aquifer were not homogeneous and isotropic; however, the variation in material properties was accounted for in the probabilistic ranges assigned to the input variables used in the discrete probabilistic analysis. The brine migration from the TMF is currently being monitored using surface electromagnetic (EM) surveys. These surveys will assist in the calibration/verification of the modelling. If significant heterogeneity exists, the EM surveys will detect an increased rate of lateral brine migration in those areas.

The flow components of the ADE are advection, diffusion and mechanical dispersion. Advective transport is the process by which the solute is transported at the rate of the interstitial groundwater velocity. Molecular diffusion is the decrease in solute concentration due to a concentration gradient, and due to the thermal kinetic energy of the particles (Brownian motion). Molecular diffusion can (and does) occur in the absence of advection. Theoretically, diffusion will continue until the concentration gradient is equal to zero. Mechanical dispersion refers to the nonsteady irreversible mixing of two miscible fluids displacing one another in a porous medium. Mechanical dispersion occurs due to microscopic velocity variations within the porous medium. Details regarding the basic theory of solute migration can be found in Freeze and Cherry (1979) and numerous other textbooks.

3.2 Advection Dispersion Equation (ADE)

The one-dimensional form of the advection-dispersion equation of nonreactive dissolved constituents in saturated, homogeneous, isotropic materials under steady state, uniform flow is as follows:

$$D \frac{\partial^2 C}{\partial l^2} - v \frac{\partial C}{\partial l} = \frac{\partial C}{\partial t}$$

where:

	l	= curvilinear coordinate direction taken along the flow line
	v	= the average interstitial groundwater velocity
	D	= the coefficient of hydrodynamic dispersion
	C	= the solute concentration
	t	= time
and	v	= $k i_{ADJ} / n$

where
- k = hydraulic conductivity
- i_{ADJ} = hydraulic gradient (adjusted to account for density differences between brine and fresh water).
- n = porosity

D = $(D^* + \alpha v)$

where
- D^* = apparent coefficient of mechanical dispersion
- α = dispersivity

For a step function input, the boundary conditions are represented mathematically as:

$C(l,0) = 0$	$l \geq 0$
$C(0,t) = C_o$	$t \geq 0$
$C(\infty,t) = 0$	$t \geq 0$

The solution to the one-dimensional ADE for the above boundary conditions is given by Ogata (1970) as:

$$\frac{C}{C_o} = \frac{1}{2}\left[erfc\left(\frac{l - vt}{2\sqrt{Dt}}\right) + \exp\left(\frac{vl}{D}\right) erfc\left(\frac{l + vt}{2\sqrt{Dt}}\right)\right]$$

where:

erfc	= the complementary error function
C_o	= initial concentration
C, l, v, t, D	= same as previously defined

A computer program was used to solve the equation given by Ogata (1970) for the concentration ratio (C/C_o) at various distances and times. A concentration ratio of 0.001 was used to define the extent of the solute plume. A discrete probabilistic simulation was used to account for variations in the input parameters (k, i_{ADJ}, D^* and α). The discrete probabilistic simulation is described in the following sections.

3.3 Probabilistic Framework

In order to quantify the uncertainty associated with our estimate of travel distances for the brine front, the ADE solute transport model was implemented with in probabilistic framework. This framework is shown in Figure 2. Note that we have chosen the terminology "framework" rather than model, because a specific software tool was not need to facilitate this particular example. However, it should be recognized that commercial "probabilistic simulation" software tools do exist, and they may be useful in other applications. For this application, the processing of the probabilistic information (the input/output from the ADE model) was using a spreadsheet.

A discrete probabilistic framework for this analysis was selected to quantify the uncertainty surrounding the input parameters for the one-dimensional ADE solute transport model. Discrete probabilistic simulation was selected over continuous probabilistic simulation as it is more efficient for problems with a limited number of state variables.

Discrete probabilistic simulation uses discrete approximations to represent the probability distributions which describe the uncertainty associated with each of the probabilistic state variables. The probabilistic state variables are simply the random variables in the numerical model being simulated that are to receive probabilistic consideration (in this example: k_h, i_{ADJ}, D^* and α). The set of probabilistic state variables and their discrete approximations define a series of possible scenarios (number of scenarios=z) for the simulation. Each scenario has a unique outcome ($d(x)_z$) and a unique probability of occurrence ($p(x)_z$). The probabilistic outcome set ($d(x)_z$, $p(x)_z$ for all (z) can be ranked by outcome and compiled into frequency or cumulative probability distributions. The total number of model runs (z) required to solve a discrete probabilistic simulation is a finite number known to the analyst prior to running the simulation. The degree of discretizing the probability distributions for each probabilistic variable can be manipulated to adjust the total number of model runs required to solve the simulation. For this study, four probabilistic state variables were modelled using a 3 branch approximation for each.

Graphically, the scenarios developed for the simulation of the ADE one-dimensional solute transport can be expressed using the decision tree shown in Figure 3. Each path through the decision tree represents one possible scenario. Multiplying the probabilities along a path through the tree gives the probability of that particular scenario occurring. The simulation is completed by calculating the outcome and associated probability for every path through the tree. For this application there were 81 possible paths through the tree; therefore, for each time step (25, 50, 75 years) the ADE model would be iterated 81 times.

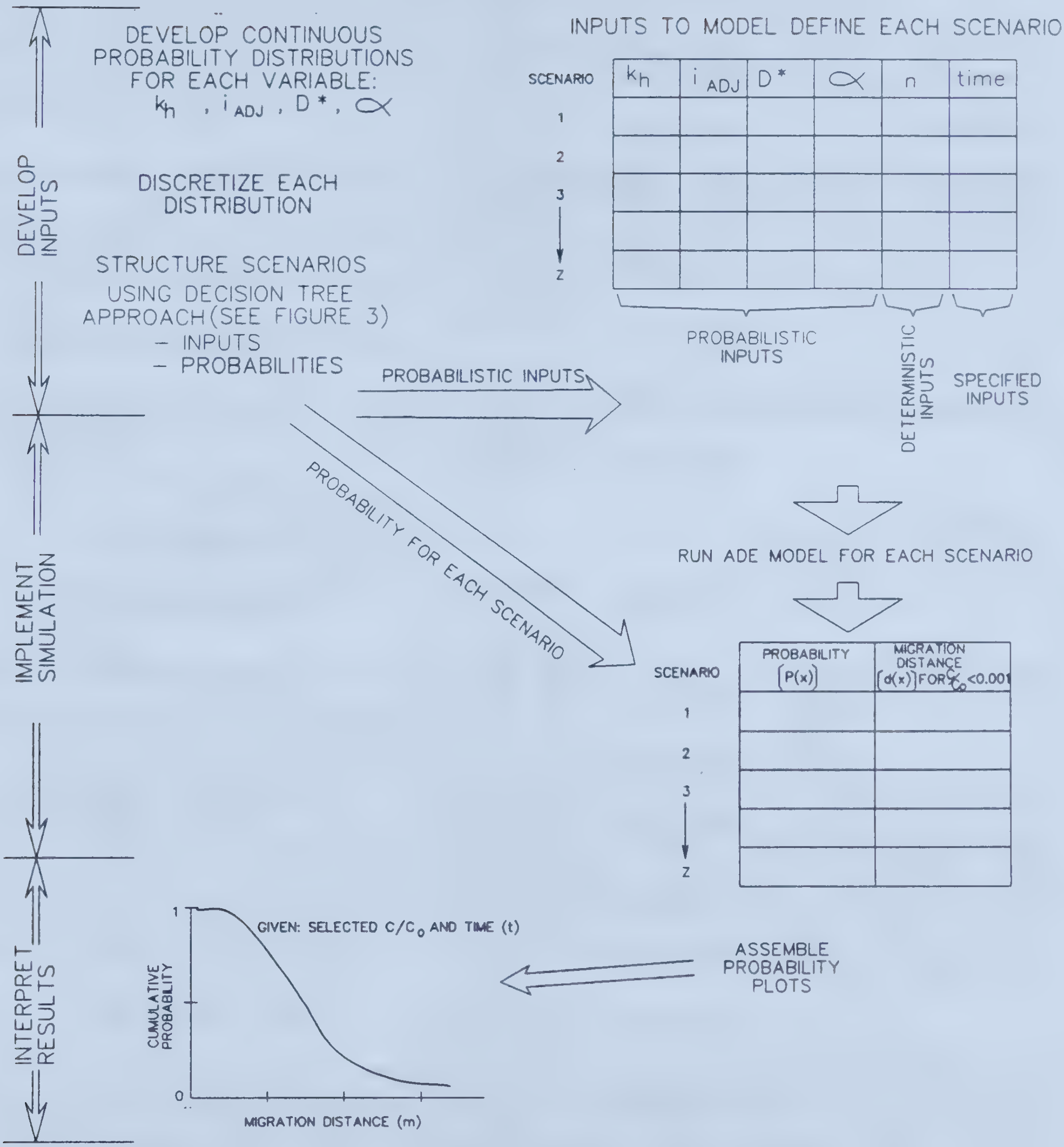

Figure 2 Probabilistic Framework

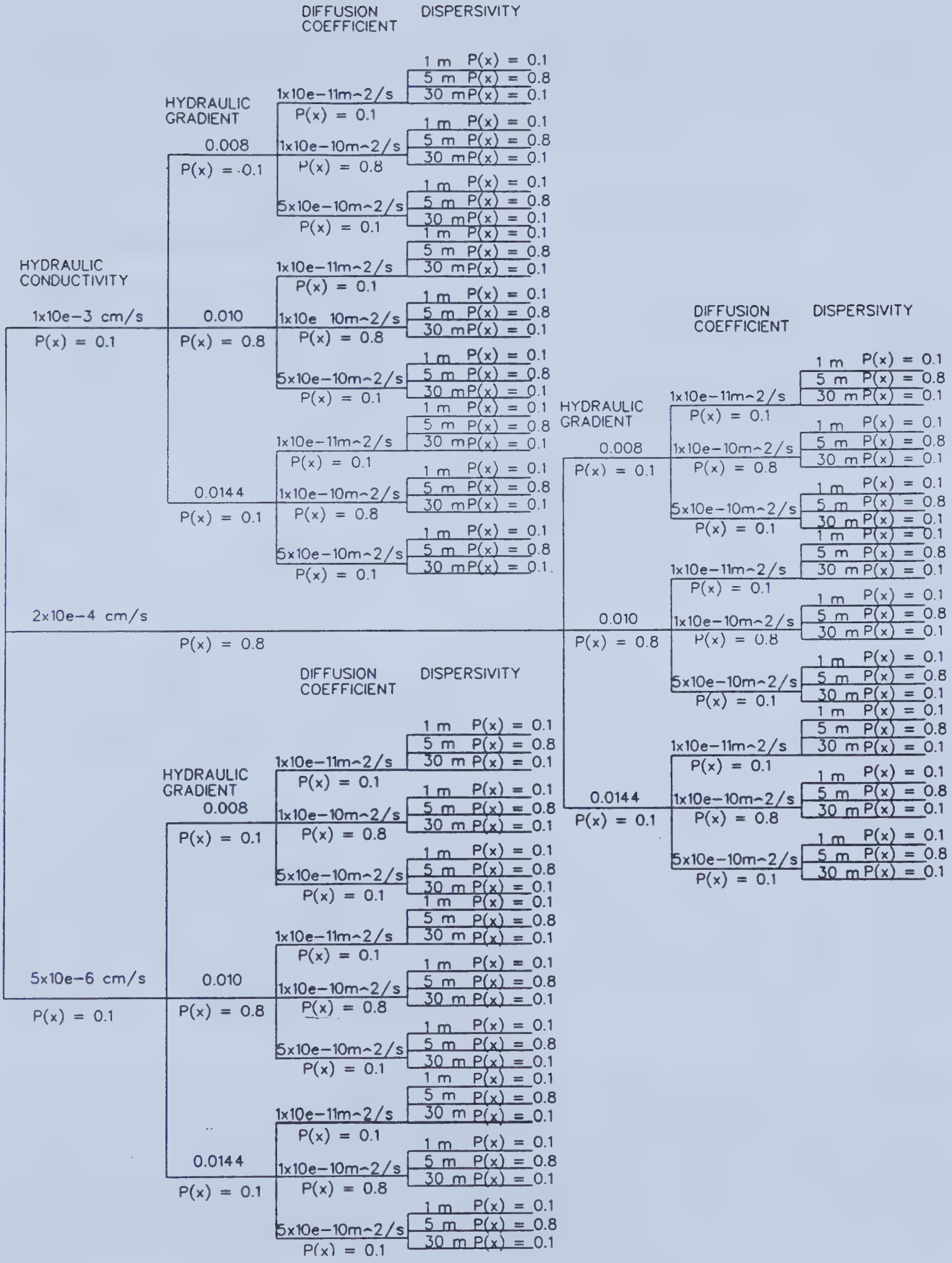

Figure 3 Decision Tree

Developing the discrete approximation for each probabilistic state variable is a two step process. First, a continuous probability function for each variable must be developed. This can be accomplished by using historical observations and generating probabilistic estimates based on relative frequency, or by encoding subjective probabilistic information. Techniques for developing probabilities based on relative frequency and subjective information are described in Kajner (1990), Gregory (1988), Bunn (1984), Holloway (1979) and Kahneman and Tversky (1974). When encoding subjective probabilities care must be exercised to avoid common heuristics and biases that may occur (Kahneman and Tversky (1974)).

Once the cumulative probability distribution is developed for each variable, it is discretized to form a discrete approximation of the cumulative distribution. This process involves creating a step function along the cumulative probability curve that balances the individual areas above and below the line. This process can be done by eye or by using calculus (Celona and McNamee (1987)).

3.3.1 Developing Probabilistic Inputs

The probabilistic variables in the ADE model were assumed to be probabilistically independent. The following four variables were modelled probabilistically:

- hydraulic conductivity, k_h
- hydraulic gradient, i_{ADJ}
- diffusion coefficient, D^*
- dispersivity, α

The porosity (n) of the soil was modelled as a deterministic input because the uncertainty associated with the estimate of n was felt to be relatively small.

The following sections provide an explanation of the rationale used in selecting the discrete probabilistic approximations for each probabilistic state variable used in the simulation. The initial step of developing a cumulative distribution for each probabilistic state variable has not been included in this paper, but is available in Kajner, Bruch and Muir (1993). For the purpose of this study, both relative frequency and subjective information were utilized in developing the probabilistic inputs for the ADE model.

3.3.1.1 Hydraulic Conductivity, k

The advective-dispersion model described previously requires an estimate of the bulk saturated horizontal hydraulic conductivity of the aquifer (k_h). This requires that the assumption is made that the soils in the aquifer are homogeneous. The actual horizontal hydraulic conductivity of the surficial aquifer will in fact vary with location and depth as a result of the varying stratigraphy of the site and the degree of disturbance of the sediments (zones of weathering, influence of vegetation, fractures, etc.). The post glacial, Lake Saskatchewan Sediments that comprise the surficial aquifer vary from an oxidized silty sand to an oxidized silty clay with a majority of the flow within the aquifer expected to occur through the oxidized silty sand zone.

In order to develop an estimate of k_h the following information sources were reviewed:

- slug tests, (part of the field program)
- triaxial hydraulic conductivity tests: Kajner and Muir (1993)
- back-calculation from EM surveys, Maathuis and van der Kamp (1983)
- published typical values, Freeze and Cherry (1979) and Holtz and Kovacs (1981)

The hydraulic conductivity estimates from the various sources are summarized in Table 1. From Table 1 it is evident that k_h of this particular soil unit may vary within a wide range of 10^{-2} cm/s to 10^{-7} cm/s. Considering that: 1) that the soils are comprised of predominantly finer grained material with typically over 80 % passing the #200 sieve, 2) the fines are low to medium plastic, 3) allowing for influence of weathering and possible fractures, and 4) allowing for the heterogeneity of the aquifer soils, the following discrete probabilistic estimate was developed for the bulk horizontal hydraulic conductivity of the aquifer:

- $k_h = 1 \times 10^{-3}$ cm/s with a probability of 0.1
- $k_h = 2 \times 10^{-4}$ cm/s with a probability of 0.8
- $k_h = 1 \times 10^{-6}$ cm/s with a probability of 0.1

Table 1 Summary of Hydraulic Conductivity Values Used to Develop Discrete Probabilistic Estimate

Material	Hydraulic Conductivity (cm/s)	Reference
Silt (Test Hole 4)	2.3×10^{-4}	Kajner, Bruch and Muir, 1993
Silt (Test Hole 7)	2.2×10^{-4}	Kajner, Bruch and Muir, 1993
Silty Clay (Test Hole 14)	9.6×10^{-6}	Kajner, Bruch and Muir, 1993
Silt (Test Hole Com 124)	1.7×10^{-4}	Kajner, Bruch and Muir, 1993
Silty Sand (Triaxial)	4.1×10^{-6}	Kajner and Muir, 1993
Medium Plastic Clay (triaxial)	1.4×10^{-7}	Kajner and Muir, 1993
Silty Sand	10^{-1} to 10^{-5}	Freeze and Cherry, 1979
Silt	10^{-3} to 10^{-7}	Freeze and Cherry, 1979
Fine Sands, Silts, Mixtures of Sand Silts and Clays, Stratified Clays	10^{-3} to 10^{-7}	Holtz and Kovacs, 1981
Impervious Soils Modified by Weathering	10^{-2} to 10^{-7}	Holtz and Kovacs, 1981
Surficial Sediments	1.7×10^{-4}	Back calculation from EM surveys by Maathuis and van der Kamp, 1983

3.3.1.2 Hydraulic Gradient, i_{ADJ}

The estimate of the hydraulic gradient (i_{ADJ}) used in the analysis is the sum of two components: 1) the estimated linear slope of the phreatic surface and 2) an estimated correction factor to implicitly consider the variations in fluid density. The estimate is an average value over the entire length of the flow path being analyzed. The flow regime responsible for transporting the brine is influenced by the density of the fluid being modelled. Because the ADE model does not "explicitly" consider density dependent flow, density effects were "implicitly" considered by converting the measured fluid head to a freshwater equivalent head. This conversion simulates a higher driving head for the denser brine fluid[1]. The derivation of the estimates for the two components of i_{ADJ} is described in detail below.

The analysis conducted in this study predicts the advancement of the brine front from its known location in 1992 (defined as point d_0). As such, much of the uncertainty associated with predicting the hydraulic gradient is reduced because the influence of the TMF on the hydraulic gradient is less pronounced beyond this location. The development of the estimates for hydraulic gradient northeast of this starting position (point d_0) considered the following factors:

- the regional groundwater flow regime and its seasonal patterns;

  Maathuis, Jaworski and Zlipko (1993) documented seasonal groundwater fluctuations in the surficial aquifer in the order 1 to 2 m. The highest groundwater levels were documented in May-July after spring recharge and the lowest levels in February-March just prior to spring recharge. Secondary recharge events were occasionally evident after major precipitation events.

  The impact of variations in the regional groundwater regime on the conclusions of this analysis will be muted by the fact that the hydraulic gradient is relative. Because Sections 15 and 22 are removed from any natural groundwater boundaries (i.e. lakes, river, groundwater divides, etc.) if the regional groundwater table is drawn down, it will be drawn down throughout the study area and the gradient will not significantly change over the flowpath being analyzed.

- the fluid level in the TMF;

  The fluid levels in the south brine pond, north brine pond and connecting ditches effect the degree of mounding of the water table (and rate of brine escape); however, its influence will be constrained by the configuration of the ditch system along the toe of the east dyke. The aquifer is considered to

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[1]Specific gravity of brine (@ 15.5°C) = 1.230

be unconfined and as such the (fluid) head at the ditch can not exceed the fluid level in the ditch (although an allowance for density must be added). It is therefore reasonable to assume that if Agrium continues to maintain the current ditch system, the mounding of groundwater table as a result of the brine levels in the TMF should not significantly exceed those measured in December 1992.

Fluid levels in the retention pond area will have a local effect on the groundwater table; however, this area is a discharge zone for the flow path being analyzed and consequently its impact on the "averaged" gradient will be minimal.

- density effects;

The estimate of the hydraulic gradient has been adjusted to reflect the increased density of the brine by increasing the hydraulic gradient by a constant. The estimate of the constant was developed by assuming that the dispersion of the brine front occurred over an average distance of 200 m. The specific gravity of the fluid was assumed to increase linearly from 1.000 at the leading edge of the brine front to 1.230 at a distance 200 m into the solute plume. The average thickness of fluid in the aquifer over the flow path being analyzed was assumed to be 4 m. Given the assumption made above, the slope of the "density" gradient was calculated to be 0.0046. This method of approximating the density effect will contribute to a pessimistic approximation of the advancement of the brine front as it applies the gradient correction over the entire flow path and not just at the advancing front of the solute plume.

All three scenarios assume the existing fluid level at d_o remains constant (as controlled by the levels in the TMF and ditch system). The average gradient scenario approximates the flow regime measured in December 1992. The following discrete probabilistic estimate was developed for the adjusted hydraulic gradient, as illustrated in Figure 4:

- $i_{ADJ} = 0.014$ with a probability of 0.1
- $i_{ADJ} = 0.010$ with a probability of 0.8
- $i_{ADJ} = 0.008$ with a probability of 0.1

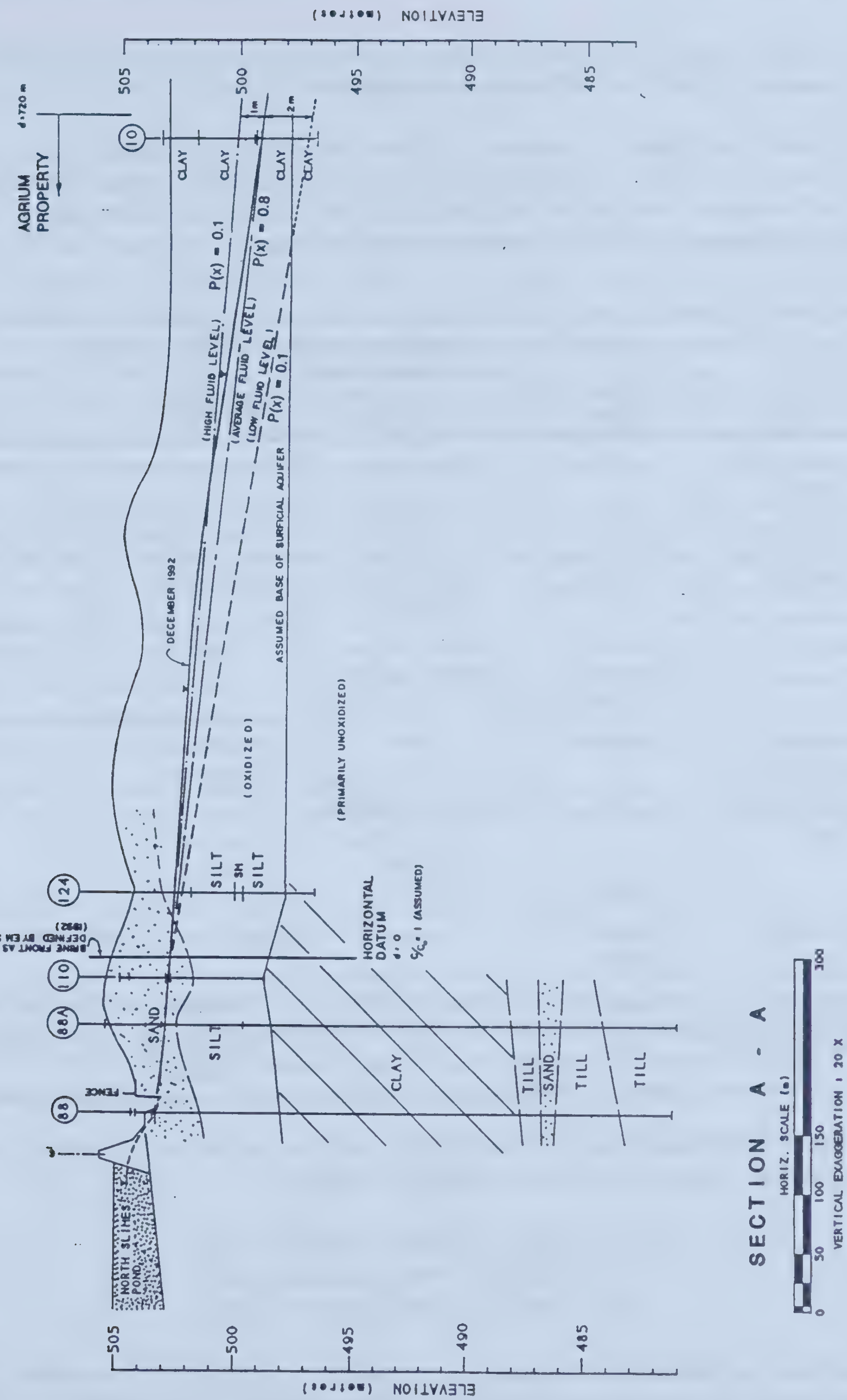

Figure 4 Illustration of Hydraulic Gradient Scenarios

3.3.1.3 Apparent Coefficient of Molecular Diffusion, D*

The apparent coefficient of molecular diffusion varies over a relatively small range, from approximately 10^{-10} to 10^{-11} m^2/s (Freeze and Cherry, 1979). Further, it must be less than or equal to the diffusion coefficient for free solution (2×10^{-9} m^2/s). A summary of apparent coefficients of molecular diffusion reported in the literature is shown in Table 2.

TABLE 2 - APPARENT COEFFICIENTS OF MOLECULAR DIFFUSION (after Barbour, 1981)

REFERENCE	SOURCE	CONTAMINANT	SOIL TYPE	D* (m^2/s)
de Josselin de Jong, 1958	Lab Test	Saline Solution	0.08 mm diameter	7×10^{-9}
Simpson, 1962	Lab Test	Indigo Carmine Dye	Porous Block	6×10^{-9}
Ogata, 1964	Lab Test	Radioactive Phosphorus	Uniform Sand	8×10^{-10}
Manheim, 1970	Lab Test reported in literature	Monovalent and Trivalent, - and + ions	Fine Sands	$2 - 6 \times 10^{-10}$
Lerman & Tangiguchi, 1972	Case History	Sr-90	Lake Sediment (Clay and Sand)	$2 - 6 \times 10^{-10}$
Goodall & Quigley, 1977	Case History Literature	Ca^+, Mg^+, K^+ and alkali Chlorides	Silty Clay	$2.2 - 13 \times 10^{-11}$ $2.4 - 4.3 \times 10^{-11}$
Freeze & Cherry, 1979	Literature Review	--------	-------	1×10^{-11} to 1×10^{-10}
Lee et al	Assumption	Saline Solution	Fine Sand	7.3×10^{-10}
Gillham et al, 1984	Lab Test	^{36}Cl	Bentonite Sand Mixture	$8-10 \times 10^{-9}$

On the basis of the values reported in the literature, the following discrete probabilistic estimate was developed for the apparent coefficient of molecular diffusion:

- $D^* = 1 \times 10^{-11}$ m^2/s with a probability of 0.1
- $D^* = 1 \times 10^{-10}$ m^2/s with a probability of 0.8
- $D^* = 5 \times 10^{-10}$ m^2/s with a probability of 0.1

The estimated probability distribution for the diffusion coefficient is somewhat pessimistic; however, due to the relatively short time frame being examined (75 years maximum), diffusion will not significantly contribute to the advance of the brine front, except at very low advective flow velocities. However; if the advective velocity is low enough to make diffusion significant, then the migration distance for the brine front would be relatively small.

3.3.1.4 Dispersivity, α

Dispersivity is a scale dependant parameter. Dispersivity in the direction of flow (longitudinal dispersivity, α_L) is generally different than the dispersivity in the direction perpendicular to the flow (transverse dispersivity, α_T). In the case of one-dimensional flow, only the longitudinal dispersivity is required. Freeze and Cherry (1979) indicate that dispersivity is "the most elusive of the solute transport parameters". Dispersivity may be back-calculated from column tests; however, due to the scale effects noted above, these values may have little relevance in the field. Field scale measurements of dispersivity can be obtained by: 1) single well withdrawal-injection tests, 2) natural gradient tracer tests, 3) two-well recirculating withdrawal-injection tests, and 4) two-well pulse tests. All of these field tests are time consuming and expensive to perform. Further, the results of these tests are dependant on the mathematical model used to calculate the dispersivity, and the scale of the test. For these reasons, the dispersivity values used in the discrete probabilistic analysis were determined on the basis of values reported in the literature. A summary of dispersivity values reported in the literature is shown in Table 3.

On the basis of the values shown in Table 3, the following discrete probabilistic estimate was developed for the dispersivity of the soils:

- $\alpha = 1$ m with a probability of 0.1
- $\alpha = 5$ m with a probability of 0.8
- $\alpha = 30$ m with a probability of 0.1

3.3.1.5 Porosity, n (Deterministic Variable)

The porosity of the soil was assumed to be a deterministic value in the simulation. An examination of the water contents from samples obtained in the field program yielded a range of porosity from approximately 0.4 to 0.5. The porosity value (n) used in the solute migration analysis was 0.45. The assumed value agrees with that reported by Maathuis Jaworski and Zlipko (1993).

TABLE 3 - DISPERSIVITY VALUES (after Barbour, 1981)			
Scale	**Method**	**Longitudinal Dispersivity (α_L), metres**	**Reference**
Small Sample (< 2m)	Column Test	0.01	Pickens et al, 1980
	Column Test	0.002	Pickens, 1980
2 - 4 m	Single well test	0.1 to 0.5	Fried, 1975
	Single Well Point Dilution Test	0.1	Pickens et al, 1980
4 - 20 m	Two-well Test	38.1	Grove and Beetem, 1971
	Multiple Well Test	4.25 to 11.0	Fried, 1975
	Two-well Test	0.5	Pickens et al, 1980
20 - 100 m	Single well test with geophysical monitoring	12.0	Fried, 1975
> 100 m (usually several km)	Modelling	61.0	Bredehoeft and Pinder, 1973
		21.3	Pinder, 1973
		91.0	Robertson and Barraclough, 1973
		30.5	Konokow and Bredehoeft, 1974
		15.0	Fried, 1975
		6.7	Segal and Pinder, 1976
		3.0 6.1	Schwartz, 1977

3.3.2 Implementation of Simulation

The analysis was conducted using a computer program to solve the ADE solute migration model for the C/C_o ratio at various distances from the existing front at elapsed times of 25, 50 and 75 years. The location of the solute front was taken as the point where C/C_o was less than 0.001. If the concentration of brine (C_o) is taken as 300 000 mg/L, then the assumed concentration at the brine front would be 300 mg/L, which corresponds to the Saskatchewan drinking water objectives (Saskatchewan Environment (1980)). Obviously, if a higher C/C_o ratio is used to define the front of the plume, the computed travel distances of the brine front would be smaller.

After the solution was generated for all 81 scenarios, at each of the three elapsed time values, the travel distance for the front of the plume was determined along with its associated probability. The trials were then ranked by migration distance and a cumulative probability distribution was computed for each elapsed time, as illustrated in Figure 5.

4.0 INTERPRETATION OF RESULTS

The cumulative probability distributions for elapsed times of 25, 50 and 75 years are shown on Figure 5. This figure shows the cumulative probability on the vertical axis and the travel distance of the brine front from d_o (current position of the brine front) on the horizontal axis. The minimum travel distance (d) for off-site brine migration to occur is approximately 720 m, as shown on the graph. The probability of off-site brine migration can be interpreted from the this figure as:

- approximately 0% probability of off-site brine migration in 25 years
- 2% probability of off-site brine migration in 50 years
- 8% probability of off-site brine migration in 75 years

The expected value for the travel distance of the solute plume would be:

- 100 m from d_o in 25 years
- 160 m from d_o in 50 years
- 215 m from d_o in 75 years

Based on the discrete probabilistic simulation of brine migration from the TMF for the reference section selected, it appears that there is only a small probability that the brine front (defined by C/C_o = 0.001) may migrate off-site, even assuming a 75 year remaining operating life. Assuming a remaining operating life of 25 years, there is no significant probability of off-site migration. Once the mine is decommissioned, the pre-mine groundwater flow regime is expected to be re-established and the migration of brine towards the northeast will be reduced.

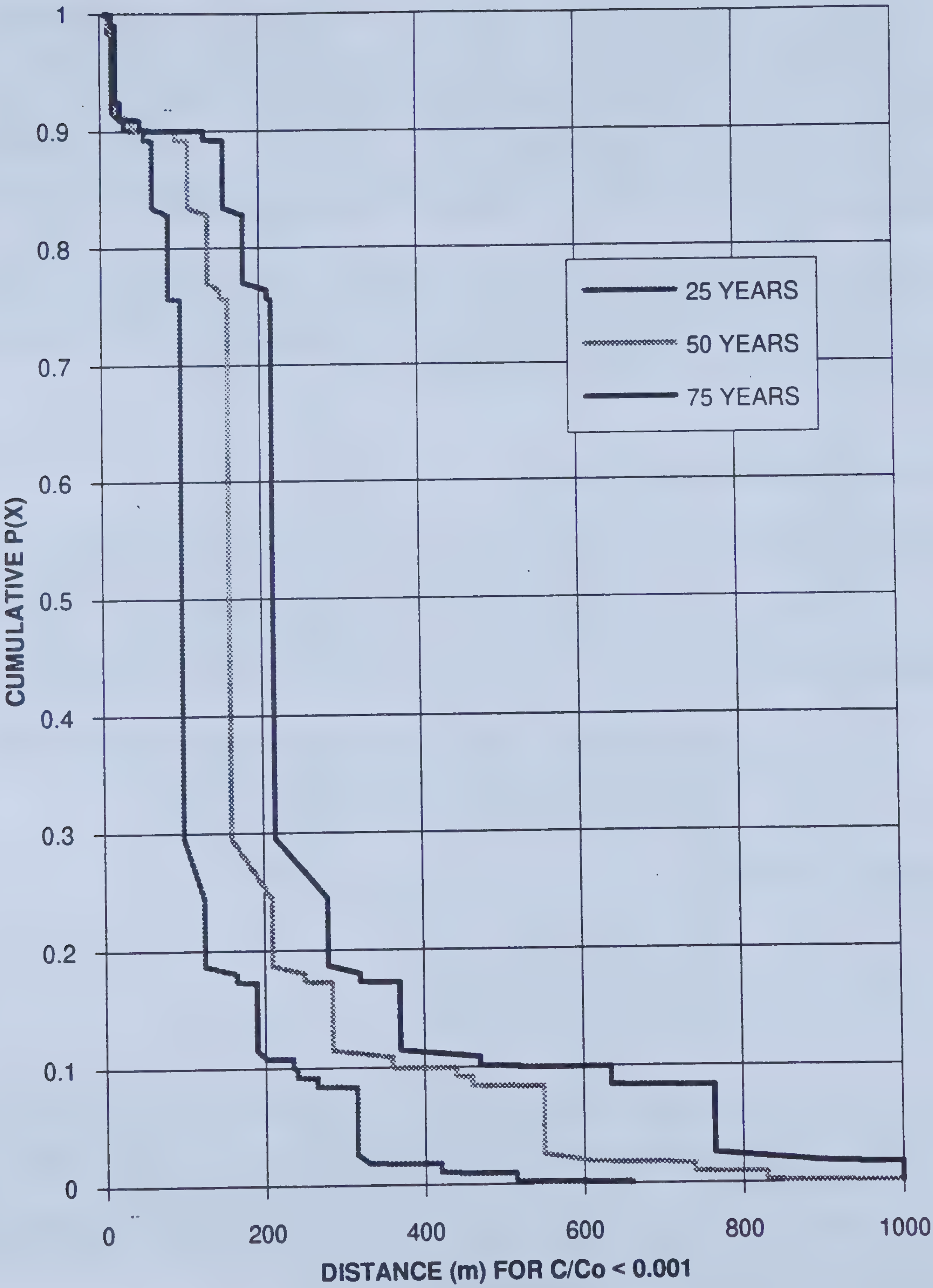

Figure 5: Cumulative Probability Distribution for Brine Front Migration

5.0 CONCLUSIONS

This paper has illustrated a practical methodology for explicitly quantifying the potential for off-site brine migration for an operating potash mine. The methodology is simple and efficient. By explicitly quantifying the uncertainty in the dominant inputs to the solute transport model and integrating this uncertainty through to the estimate of travel distance using discrete probabilistic simulation, the analysts were able to explicitly quantify the expected value and the uncertainty in our estimates. This is clearly a more robust answer than would have been achieved using a deterministic analysis framework.

The analysis utilized a relatively simple solute transport model and simplifying assumptions regarding the soil stratigraphy and other inputs. If this first order calculation had indicated a significant potential for off-site brine migration, further analyses would have been undertaken. Using a relatively simple model within a probabilistic framework provided a technically sound analysis in a cost efficient manner.

The brine migration in the area under consideration is currently being monitored using surface electromagnetic (EM) surveys. These surveys will assist in the calibration/verification of the modelling.

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