Equilibrium Environmental Inc.

PROJECT STUDY FOR THE DEVELOPMENT OF GENERIC SITE ASSESSMENT CRITERIA FOR SALINITY BELOW THE ROOT ZONE

REPORT ON SALT TRANSPORT MODEL SENSITIVITY ANALYSIS RESULTS

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EXECUTIVE SUMMARY

E-1.0 Introduction

This report details the methodology and results of a sensitivity analysis conducted by Equilibrium Environmental Inc. (Equilibrium) in support of the salt transport modeling portion of the Petroleum Technology Alliance Canada (PTAC) "*Project Study for the Development of Generic Site Assessment Criteria for Salinity below the Root Zone*". Saline water can be released to the environment as a result of oil and gas production activities and operation of road salt storage facilities. The infiltration of saline water into soil may have negative effects on plant growth, shallow groundwater quality, and soil hydraulic conductivity. Alberta Environment's site assessment criteria for soil salinity currently exist for the 0 to 1.5 m soil depth interval (topsoil and shallow subsoil). This depth interval is commonly referred to as the root zone. The PTAC project study was conceived with the ultimate goal of deriving generic site assessment criteria for salinity at depths below the root zone.

In order to reach this goal, a sensitivity analysis was conducted to better understand factors that influence salt transport in soil within and below the root zone. Those factors that are the most influential for determining salt transport will also be key determinants in the development of deep subsoil criteria. Salt transport modeling within the vadose (unsaturated) zone and shallow saturated zone was performed using public-domain computer software specifically designed for this purpose (*e.g.*, HYDRUS and LEACHM).

E-2.0 Factor Selection

Model input factors were identified that were considered relevant to salt transport and water balance in shallow soil. Eleven input factors were selected:

Input Factor	Low Boundary Value	High Boundary Value
1. Climatic Moisture Index	-627 mm (Medicine Hat)	82 mm (Whitecourt)
2. Source Depth for Release	Surface	2 m
3. Upper Soil Lithology	Fine	Coarse
4. Lower Soil Lithology	Fine	Coarse
5. Upper Lithology Layer Thickness	2 m	4 m
6. Interbedding of Fine / Coarse Soils	None	Interbedded 0.5 m
7. Deep Drainage Boundary Condition	12 mm/year	Free Drainage
8. Vegetation Presence	None	Full Cover
9. Root Depth	0.5 m	1.5 m
10. Slope Induced Runoff	None	5% Slope
11. Longitudinal Dispersivity	100 mm	500 mm

Model input factors were varied between high and low boundary values. These boundary values are considered representative of typical conditions for Alberta. Values that would occur outside of these ranges can be evaluated as special cases during the generic criteria matrix development process. The high and low boundary value was alternately varied based on the run design discussed in the Methodology section of the Main Report.

Climate Moisture Index

The climate moisture index (CMI) is a measure of the difference between annual precipitation and annual potential evapotranspiration. The formula for CMI is:

$$CMI = P - PET$$

where,
P = average total annual precipitation (mm); and,
PET = average total annual potential evapotranspiration (mm).

The two boundary CMI values were taken from the Whitecourt climate station near the Swan Hills area and the Medicine Hat climate station. The CMI for Whitecourt was calculated to be +82 mm, based on an average annual precipitation of 578 mm (taken from the Canadian Climate Normals Database; Environment Canada, 2000) and an average annual potential evapotranspiration of 496 mm (taken from the Canadian Ecodistrict Climate Normals Database; AAFC, 1999). The CMI for Medicine Hat was calculated to be -627 mm, with an average annual precipitation of 334 mm and an average annual potential evapotranspiration of 961 mm. These values are within the upper and lower bounds of the range of possible CMI values for Alberta (*i.e.*, +150 mm to -689 mm).

Source Depth for Release

The depth of the saline source of impact was determined based on experience with the release scenarios of interest outlined in the PTAC study scope of work (*i.e.*, pipeline breaks, flare pits, and salt storage facilities). A surface source and a source centered at 2 m depth (1.75 to 2.25 m) were selected. The surface source was considered representative of a salt storage facility source or a pipeline break source that has migrated to the soil surface. The 2 m depth source was considered representative of a flare pit base or a pipeline break at depth.

Upper and Lower Soil Lithology

The simulated soil column was divided into upper and lower sections to provide a means for investigating the effects of varying texture on salt transport. Soils were grouped into two general texture categories (*i.e.*, coarse and fine). Varying combinations of layering were considered, such as coarse over fine, fine over coarse, and uniform columns of fine or coarse soils. The reader is referred to Figure 1 in the Main Report for an illustration of the different soil lithology scenarios used in the sensitivity analysis modeling.

Reasonable boundary conditions were established to accommodate the majority of soil texture classifications at saline release sites while avoiding model instability caused by the layering of “extreme” differences in texture (*e.g.*, coarse well sorted gravel overlying swelling clay). Based on an analysis of the Agricultural Region of Alberta Soils Inventory Database (AGRASID; Alberta Agriculture Food and Rural Development (AAFRD), 2004), 23,396 records exist in the database for mineral (non-organic) soils. Of the following coarser grained soils: sand; loamy sand; and sandy loam, 76% (2,158 out of 2,857) were sandy loam soils. For finer grained soils, clay loam was reported for 4,701 records with 492 records for clay and 226 records for heavy clay. For these three fine textured soils 87% (4,701 out of 5,419) were clay loam soils. Therefore the two boundary values selected for the coarse and fine texture soil categories were sandy loam and clay loam soils, respectively. These soil textures were considered representative of the majority of soil texture groupings expected to be present at saline impacted sites.

Upper and Lower Soil Lithology Layer Thickness

Two upper soil lithology layer thicknesses were considered to evaluate the effect of general texture layering that could be expected at saline impacted sites. These thicknesses were 2 or 4 m of coarse or fine soil overlying the lower soil lithology layer. The thickness of the lower soil layer was the difference between 10 m (maximum soil depth considered in the model) and the upper soil layer thickness.

Interbedding of Fine and Coarse Soils

The importance of relatively thin interbedded layers of fine and coarse soils on the net bulk transport of salts was examined. The thickness of each interbedded layer was assumed to be 0.5 m. The sensitivity of the model output to the presence or absence of an interbedded soil texture column was established by comparing against the model results for a soil column without interbedding.

Drainage Boundary Condition

The drainage boundary condition is defined as the net downward rate of water flux that exits the base of the modeled soil column where a domestic useable aquifer was hypothetically assumed to be located. This condition controls the depth of the water table, and thus the thickness of the saturated zone, for a given soil column. Situations with a high drainage rate lead to a deeper water table and relatively thin saturated zone. Situations with a low drainage rate lead to a shallower water table and thick saturated zone. Two drainage rates were considered: a low drainage rate of 12 mm/yr considered representative of a fine soil layer overlying a domestic useable aquifer (DUA), the reported drainage rate for clay till in Alberta (Alberta Environment, 2001); and, a high or “free” drainage rate considered representative of a situation where a deeper and relatively low permeability layer is assumed to not be present between the depth of saline impacted soils and the water table. The predicted drainage rate in the free drainage scenario varied between model runs (*i.e.*, rates ranged from 6 mm/yr to 190 mm/yr) since it was controlled by multiple variables (*e.g.*, net moisture infiltration, the presence of plants, soil texture and associated drainage in the saturated zone of the modeled soil column, *etc.*). Results from this component of the sensitivity analysis were also used to develop a relationship between peak chloride transport depth and drainage rate at the lower boundary of the modeled soil column (discussed in Section E-6).

Vegetation Presence and Root Depth

The vegetation presence factor is an important variable that in part determines the role of water balance in topsoil and shallow subsoil (0 to 1.5 m depth) on the net transport of salts. The root system of the plants provides a mechanism of water removal from the soil column throughout the root zone by the process of transpiration. Situations where plant growth is absent lead to water removal from the soil column solely through the process of evaporation at the soil surface. Two root depths were also considered (0.5 and 1.5 m). These depths were assumed to be representative of the typical maximum root depth of agricultural plants and native plant species found in various ecoregions of Alberta (*e.g.*, boreal forest, grasslands). The two boundary values simulated for vegetation presence were 100% and zero plant cover.

Slope Induced Runoff

The effect of ground slope on generating runoff from available precipitation was investigated to determine the magnitude of influence on net salt transport. Ground slope can affect salt transport by reducing the amount of water that infiltrates into the soil column. Boundary conditions of 0 and 5% slope were selected. A 5% slope was considered to be a reasonable upper limit for the variability of ground slopes at salt impacted sites as well as a defining point below which vertical transport is likely to be the predominant vector. For steeper slopes, it can be expected that horizontal transport would be a significant vector, which would complicate the interpretation of results for a sensitivity analysis focused on vertical salt transport.

Longitudinal Dispersivity

Dispersion is the process of mechanical spreading of the center of solute mass due to tortuosity of the soil pore space causing variations in the flow velocity. Not all flow paths through soil pores are of equal length or size. These differences in flow velocity cause spreading of the center of solute mass. Longitudinal (in the direction of groundwater flow) dispersivity is used to represent the effect of variations in groundwater flow velocity on solute concentration.

Longitudinal dispersivity has been shown to increase with increasing scale of the transport medium. In other words, for longer contaminant transport distances a larger longitudinal dispersivity coefficient should be used. Regression equations produced by Schultze-Makuch (2005) were used to gain an estimate of the upper and lower limits on the range of expected longitudinal dispersivity values. Using a lower estimate for transport length of 1 m and an upper estimate for transport length of 10 m, longitudinal dispersivities of 130 and 550 mm were calculated. From these calculated results, a lower longitudinal dispersivity limit of 100 mm and an upper limit of 500 mm were selected for use in the sensitivity analysis.

E-3.0 Response Variable Definition

To determine the sensitivity of the model results to each of the eleven input factors, a number of response variables were defined. The response variables are the measured results on which data analysis was conducted to determine relative sensitivity. The response variables serve as benchmarks from which information regarding the salt transport behaviour can be determined for different model scenarios and were selected based on their relevance to describing effects on salt transport and water balance in the soil column. Response variables related to chloride transport were measured after a 10-year simulation duration. The response variables were:

Model responses related to chloride transport
- depth to peak soil chloride concentration;
- peak magnitude of soil chloride concentration;
- breakthrough depth for 250 mg/L soilwater chloride concentration;
- maximum soil chloride concentration in the 0 to 1.5 m depth interval;
- depth of maximum soil chloride concentration in the 0 to 1.5 m depth interval;

Model responses related to water balance
- annual deep drainage of the soil column;
- annual surface runoff;
- maximum annual water table depth; and,
- minimum annual water table depth.

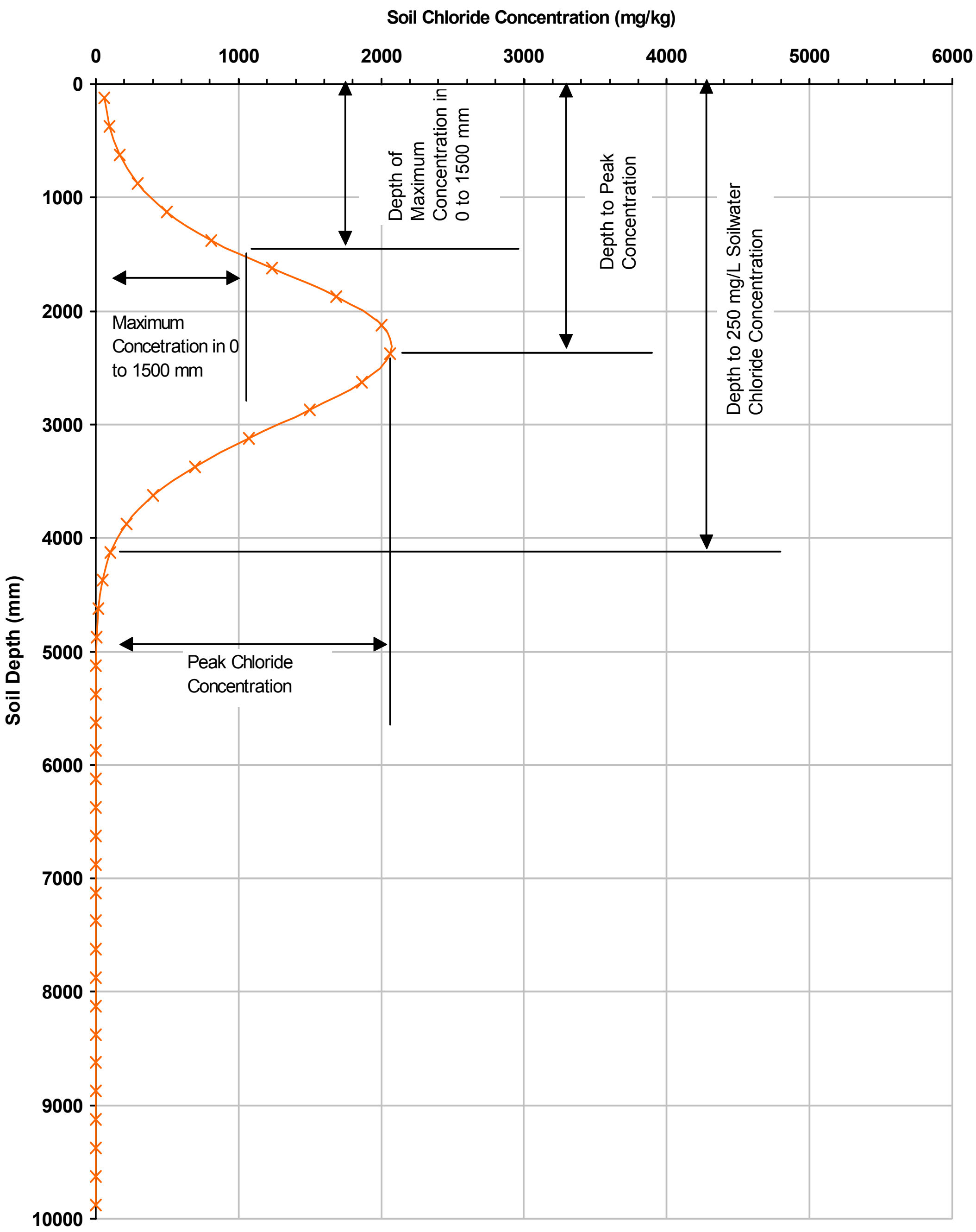

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Figure E-1. Definition of Chloride Modeling - Measured Response Variables	**09/20/2005**	**Sensitivity Analysis**
	Drawn by: MVC	**Job#: PT-02**

Response variable describing the shape or depth of the 10-year chloride profile are illustrated in Figure E-1.

E-4.0 Methodology

The methodology chosen for the sensitivity analysis was based on a two-value factorial design. Thereby two boundary values were tested for each input factor. A fractional factorial design was used to reduce the high number of runs required for a full factorial design with eleven input factors. A fractional factorial design prescribes that multiple factors are tested simultaneously as opposed to testing each factor independently. The number of runs performed for the fractional factorial design was 128 as compared to 2048 for a full factorial design. The sensitivity of a particular response variable is calculated as the difference between mean responses at each of the high and low boundary values. For example, the mean depth to chloride peak is calculated for the high boundary value of climate moisture index (Whitecourt) and then subtracted from the mean depth to chloride peak for the low boundary value of moisture index (Medicine Hat). The difference between the means is the sensitivity of the depth to chloride peak for the climate moisture index factor.

E-5.0 Salt Transport Modeling

Chloride transport was modeled in a one-dimensional (vertical) soil column using a numerical model solving Richard's equation for water flow in an unsaturated medium coupled with solution of the convection dispersion equation. Modeling was completed using the LEACHM software package, which proved to be more amenable to performing batch runs due to its high numerical stability. HYDRUS-1D was used to produce a time series comprised of rainfall and snowmelt events for input into the LEACHM model runs. The use HYDRUS-1D may be examined in subsequent portions of this study, such as for cation modeling, if the model convergence issues can be sufficiently addressed. However, the increased effort to achieve stable model runs was significant with HYDRUS-1D, and therefore LEACHM proved to be better suited to the large range in input factors used in the sensitivity analysis. Model runs of similar scenarios using these models produced similar results.

The salt transport modeling performed for the sensitivity analysis involved a simple one-time release of chloride-rich water. The input mass of chloride was selected to be 600 mg/cm^2, which corresponds to an approximate solution concentration of 30,000 to 35,000 mg/L (depending on soil porosity) applied to a soil thickness of 500 mm. The chloride-rich water was applied at the start of the model simulation over two depth intervals of 0 to 0.5 m and 1.75 to 2.25 m. A total of 128 runs were completed for the salt transport modeling. For each run, a stable water balance was achieved using a 20 year simulation time and a criterion of 1% annual water mass balance. The stable water balance was used as input into the chloride transport run. A criterion for acceptable chloride mass balance error of 1% over 10 years was used.

E-6.0 Sensitivity Analysis Results

Significance testing by pooled t-test was conducted on calculated model sensitivities to determine the statistical level of significance of the results. The significance ranking from the t-test results is summarized below:

- Highly sensitive input factors were assigned a significance level of 5%;
- Moderately sensitive input factors were assigned a significance level of 10%; and,

- Low or negligibly sensitive input factors were classified as such if they were not significant at the 10% level.

A relative sensitivity was developed by assigning a value of 100% to the most sensitive main effect. The relative sensitivity for subsequent effects was calculated as a percentage of the most sensitive effect.

E-6.1 Main Effects

The main sensitivity effects were calculated by examining the effects of one factor influencing the model response at a time. The sensitivity results for main effects are ranked from most sensitive to least sensitive in Table E-1, and detailed results are contained in Appendix A (Table A-3). The relative sensitivity for each factor was calculated from the maximum sensitivity response (equal to 100%).

Three model responses were used to describe the depth of the transported chloride profile: depth of the peak chloride concentration; breakthrough depth for 250 mg/L chloride concentration; and, depth of the maximum chloride concentration in the 0 to 1.5 m depth interval. The top three factors influencing the depth of all three of the chloride responses were: 1) the drainage boundary condition; 2) source depth of release; and 3) climate moisture index, in varying order depending on which of the three depth responses was examined. The importance of the drainage boundary condition to the migration depth of the profile peak is illustrated in Figure E-2, which shows the regression relationships between annual drainage rate and depth of the chloride peak. The relationship has been subdivided into surface and 2 m source depths.

E-6.2 Interaction Effects

Interaction effects are the result of combined effects between two or more factors on model response. First-order interaction effects (combined effects of two factors) were investigated in this report. The results indicate few first-order interaction effects produced sensitivities at the statistically significant levels of 5 or 10%. The interaction effects that were detected were not greater than the maximum main effects. Therefore, calculation of interaction effects higher than first-order was not undertaken. A total of 55 first-order interaction effects are possible between the 11 input factors. The top ten interaction effects are contained in Table E-2 for each of the measured model responses.

The magnitudes of the top ten interaction effects (details in Appendix A, Table A-4 of Main Report) are within a range of 6 to 87 % of the maximum main effect. Therefore, the interaction effects are not larger than the maximum main effects. The number of statistically significant interactions at the 5% level is between none and four. This indicates that the number of significant interactions is low. Generally, interactions between model variables are of lesser importance that the effect of individual variables, in terms of model sensitivity.

Table E-1. Main Effects Sensitivity Rankings for Model Responses

Ranking	Depth to Peak			Peak Concentration			Breakthrough Depth for 250 mg/L Concentration		
	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking
1	Drainage BC	100%	High	CMI	100%	High	CMI	100%	High
2	Source Depth	93%	High	Dispersivity	95%	High	Drainage BC	85%	High
3	CMI	80%	High	Upper Lithology	59%	High	Source Depth	53%	High
4	Vegetation Presence	32%	Moderate	Vegetation Presence	57%	High	Upper Lithology	43%	High
5	Upper Lithology	32%	Moderate	Source Depth	35%	Moderate	Dispersivity	42%	High
6	Lower Lithology	6.4%	Low to Negligible	Lower Lithology	23%	Low to Negligible	Vegetation Presence	33%	Moderate
7	Root Depth	2.5%	Low to Negligible	Interbedded	21%	Low to Negligible	Lower Lithology	22%	Low to Negligible
8	Slope Runoff	2.2%	Low to Negligible	Root Depth	20%	Low to Negligible	Interbedded	13%	Low to Negligible
9	Upper Lithology Thickness	0.9%	Low to Negligible	Drainage BC	14%	Low to Negligible	Root Depth	11%	Low to Negligible
10	Interbedded	0.9%	Low to Negligible	Upper Lithology Thickness	8.6%	Low to Negligible	Slope Runoff	1.4%	Low to Negligible
11	Dispersivity	0.4%	Low to Negligible	Slope Runoff	8.2%	Low to Negligible	Upper Lithology Thickness	0.7%	Low to Negligible

Notes: Refer to Section 7 for description significance ranking and relative sensitivity.
CMI stands for Climate Moisture Index.

Table E-1 Cont'd. Main Effects Sensitivity Rankings for Model Responses

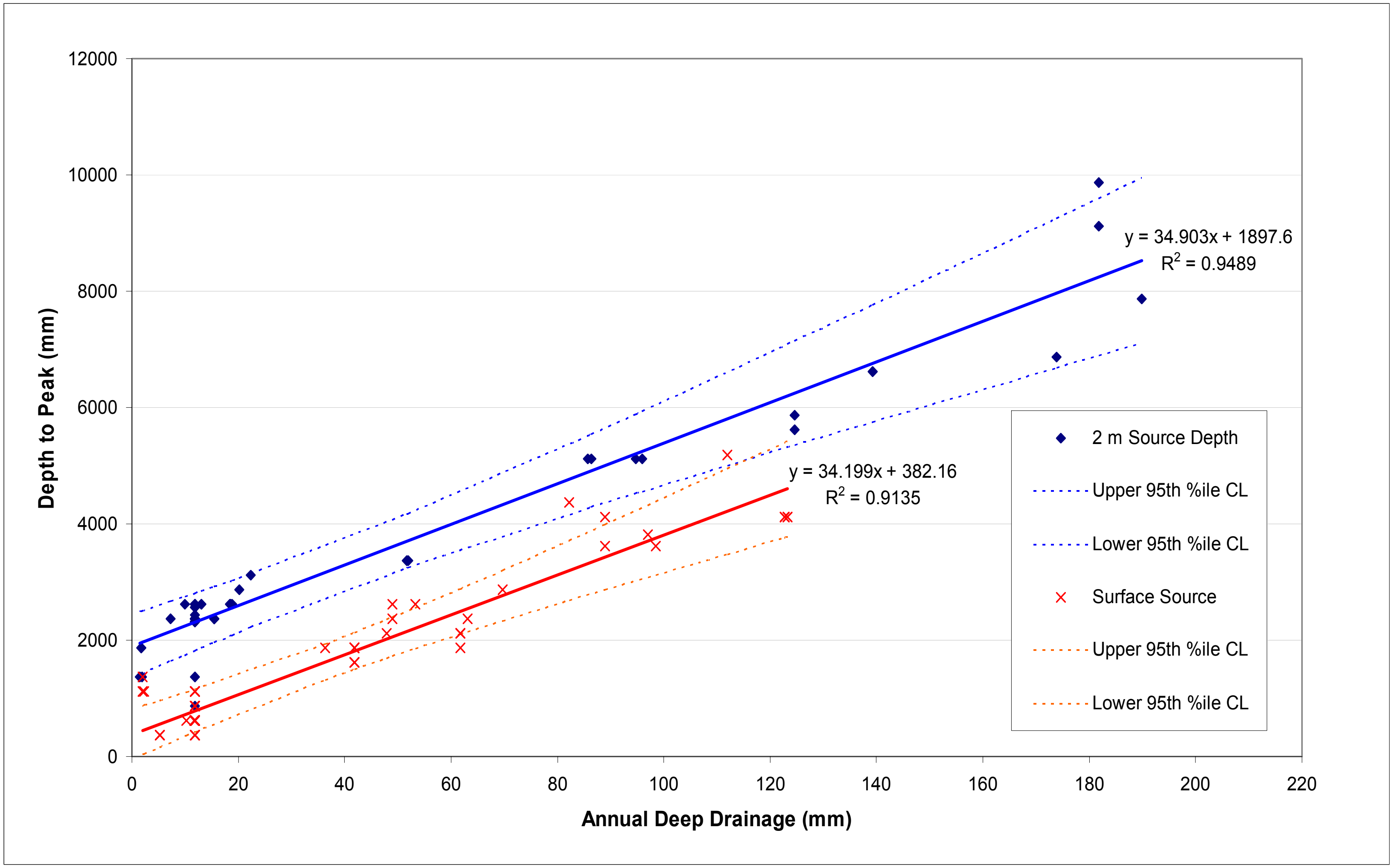
Ranking	Maximum Concentration 0 to 1.5 m			Depth of Maximum Concentration 0 to 1.5 m			Annual Deep Drainage		
	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking
1	Source Depth	100%	High	Source Depth	100%	High	Drainage BC	100%	High
2	CMI	79%	High	Drainage BC	55%	High	CMI	87%	High
3	Drainage BC	47%	High	CMI	33%	High	Vegetation Presence	40%	High
4	Vegetation Presence	47%	High	Upper Lithology	18%	Low to Negligible	Upper Lithology	31%	Moderate
5	Upper Lithology	43%	High	Vegetation Presence	14%	Low to Negligible	Root Depth	8.3%	Low to Negligible
6	Dispersivity	26%	Low to Negligible	Dispersivity	6.7%	Low to Negligible	Interbedded	5.3%	Low to Negligible
7	Root Depth	16%	Low to Negligible	Lower Lithology	3.3%	Low to Negligible	Source Depth	4.3%	Low to Negligible
8	Lower Lithology	6.4%	Low to Negligible	Upper Lithology Thickness	2.5%	Low to Negligible	Lower Lithology	2.8%	Low to Negligible
9	Interbedded	6.2%	Low to Negligible	Slope Runoff	2.5%	Low to Negligible	Slope	2.3%	Low to Negligible
10	Upper Lithology Thickness	5.2%	Low to Negligible	Root Depth	2.0%	Low to Negligible	Dispersivity	1.5%	Low to Negligible
11	Slope Runoff	4.8%	Low to Negligible	Interbedded	1.6%	Low to Negligible	Upper Lithology Thickness	1.1%	Low to Negligible

Notes: Refer to Section 7 for description significance ranking and relative sensitivity.
CMI stands for Climate Moisture Index.

Table E-1 Cont'd. Main Effects Sensitivity Rankings for Model Responses

Ranking	Annual Surface Runoff			Minumum Water Table Depth			Maximum Water Table Depth		
	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking
1	CMI	100%	High	Drainage BC	- -	High (estimated)	Drainage BC	- -	High (estimated)
2	Drainage BC	55%	High	CMI	100%	High	CMI	100%	High
3	Upper Lithology	19%	Low to Negligible	Upper Lithology	22%	Low to Negligible	Upper Lithology	40%	High
4	Interbedded	11%	Low to Negligible	Upper Lithology Thickness	8.7%	Low to Negligible	Interbedded	7.9%	Low to Negligible
5	Lower Lithology	6.8%	Low to Negligible	Lower Lithology	8.2%	Low to Negligible	Source Depth	5.9%	Low to Negligible
6	Vegetation Presence	1.2%	Low to Negligible	Source Depth	8.2%	Low to Negligible	Dispersivity	5.9%	Low to Negligible
7	Upper Lithology Thickness	0.7%	Low to Negligible	Vegetation Presence	4.8%	Low to Negligible	Slope Runoff	5.6%	Low to Negligible
8	Slope Runoff	0.3%	Low to Negligible	Dispersivity	4.8%	Low to Negligible	Vegetation Presense	4.5%	Low to Negligible
9	Dispersivity	0.3%	Low to Negligible	Interbedded	2.1%	Low to Negligible	Lower Lithology	4.1%	Low to Negligible
10	Source Depth	0.3%	Low to Negligible	Root Depth	1.3%	Low to Negligible	Upper Lithology Thickness	3.7%	Low to Negligible
11	Root Depth	0.2%	Low to Negligible	Slope Runoff	1.0%	Low to Negligible	Root Depth	0.2%	Low to Negligible

Notes: Refer to Section 7 for description significance ranking and relative sensitivity.
CMI stands for Climate Moisture Index.



PTAC	**EQUILIBRIUM ENVIRONMENTAL**	
Figure E-2. Deep Drainage versus Depth to Peak Chloride Concentration	**09/15/2005**	**Sensitivity Analysis**
	Drawn by: MVC	**Job#: PT-02**

Table E-2. Top Ten Interaction Effects Sensitivity Rankings for Model Responses

Ranking	Depth to Peak			Peak Concentration			Breakthrough Depth for 250 mg/L Concentration		
	Factor	**Relative Sensitivity**	**Significance Ranking**	**Factor**	**Relative Sensitivity**	**Significance Ranking**	**Factor**	**Relative Sensitivity**	**Significance Ranking**
1	CMI and Drainage BC	78%	High	CMI and Drainage BC	66%	High	CMI and Drainage BC	78%	High
2	Upper Lithology and Drainage	34%	Moderate	Drainage BC and Vegetation Presence	54%	High	Drainage BC and Vegetation Presence	29%	Moderate
3	Lower Lithology and Slope	29%	Low to Negligible	Source Depth and Upper Lithology	40%	High	Upper Lithology and Interbedded	23%	Low to Negligible
4	Drainage and Vegetation Presence	27%	Low to Negligible	CMI and Vegetation Presence	33%	Moderate	Lower Lithology and Slope	20%	Low to Negligible
5	Upper Lithology and Interbedded	26%	Low to Negligible	Source Depth and Vegetation Presence	28%	Low to Negligble	CMI and Interbedded	19%	Low to Negligible
6	Upper Lithology and Vegetation Presence	25.8%	Low to Negligible	CMI and Interbedded	22%	Low to Negligble	CMI and Upper Lithology	17%	Low to Negligible
7	Source Depth and Vegetation Presence	23.8%	Low to Negligible	Vegetation Presence and Root Depth	21%	Low to Negligble	Upper Lithology and Drainage	14%	Low to Negligible
8	CMI and Upper Lithology	21.4%	Low to Negligible	Interbedded and Drainage BC	20%	Low to Negligble	Root Depth and Dispersivity	14%	Low to Negligible
9	CMI and Source Depth	14.0%	Low to Negligible	CMI and Upper Lithology	19%	Low to Negligble	CMI and Dispersivity	13%	Low to Negligible
10	Lower Lithology and Drainage	11.9%	Low to Negligible	Drainage BC and Root Depth	16.8%	Low to Negligble	CMI and Lower Lithology	12.9%	Low to Negligible

Notes: Refer to Section 7 for description significance ranking and relative sensitivity.
CMI stands for Climate Moisture Index.

Table E-2 Cont'd. Top Ten Interaction Effects Sensitivity Rankings for Model Responses

Ranking	Maximum Concentration 0 to 1.5 m			Depth of Maximum Concentration 0 to 1.5 m			Annual Deep Drainage		
	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking
1	CMI and Drainage BC	72%	High	Source Depth and Drainage BC	63%	High	CMI and Drainage BC	87%	High
2	Source Depth and Upper Lithology	62%	High	CMI and Source Depth	32%	High	Drainage BC and Vegetation Presence	40%	High
3	Drainage BC and Vegetation Presence	43%	High	Upper Lithology and Root Depth	15%	Low to Negligible	Upper Lithology and Drainage BC	30%	Moderate
4	CMI and Vegetation Presence	37%	High	Source Depth and Vegetation Presence	15%	Low to Negligible	Lower Lithology and Slope	26%	Low to Negligible
5	CMI and Source Depth	33%	Moderate	Interbedded and Vegetation Presence	15%	Low to Negligible	Upper Lithology and Interbedded	23.4%	Low to Negligible
6	Source Depth and Dispersivity	24%	Low to Negligible	CMI and Vegetation Presence	12.9%	Low to Negligible	Upper Lithology and Vegetation Presence	17.0%	Low to Negligible
7	Lower Lithology and Slope	20%	Low to Negligible	Upper Lithology and Slope	12.9%	Low to Negligible	CMI and Source Depth	17.0%	Low to Negligible
8	Upper Lithology and Vegetation Presence	20.0%	Low to Negligible	CMI and Interbedded	12.9%	Low to Negligible	Source Depth and Vegetation Presence	14.9%	Low to Negligible
9	Vegetation Presence and Root Depth	19.1%	Low to Negligible	Source Depth and Upper Lithology	12.5%	Low to Negligible	CMI and Upper Lithology	14.9%	Low to Negligible
10	CMI and Dispersivity	18.3%	Low to Negligible	Vegetation Presence and Root Depth	12.1%	Low to Negligible	CMI and Vegetation Presence	12.8%	Low to Negligible

Notes: Refer to Section 7 for description significance ranking and relative sensitivity.
CMI stands for Climate Moisture Index.

Table E-2 Cont'd. Top Ten Interaction Effects Sensitivity Rankings for Model Responses

Ranking	Annual Surface Runoff			Minumum Water Table Depth			Maximum Water Table Depth		
	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking
1	CMI and Drainage BC	55%	High	CMI and Lower Lithology	33%	High	CMI and Lower Lithology	24%	Low to Negligible
2	Upper Lithology and Interbedded	26%	High	Upper Lithology and Interbedded	20%	Low to Negligible	Upper Lithology and Interbedded	20%	Low to Negligible
3	Lower Lithology and Slope	26%	High	Upper Lithology and Slope	17%	Low to Negligible	CMI and Upper Lithology	20%	Low to Negligible
4	CMI and Upper Lithology	18%	Low to Negligible	Interbedded and Slope	14.6%	Low to Negligible	Source Depth and Vegetation Presence	20%	Low to Negligible
5	CMI and Interbedded	11.6%	Low to Negligible	Lower Lithology and Interbedded	12.4%	Low to Negligible	Upper Lithology and Slope	17%	Low to Negligible
6	Interbedded and Drainage BC	8.3%	Low to Negligible	Lower Lithology and Slope	9.6%	Low to Negligible	Lower Lithology and Interbedded	16%	Low to Negligible
7	Root Depth and Dispersivity	8.3%	Low to Negligible	Upper Lithology Thickness and Slope	9.3%	Low to Negligible	Lower Lithology and Slope	12%	Low to Negligible
8	Lower Lithology and Interbedded	6.6%	Low to Negligible	Source Depth and Dispersivity	9.3%	Low to Negligible	Vegetation Presence and Dispersivity	8%	Low to Negligible
9	Upper Lithology and Slope	6.6%	Low to Negligible	CMI and Upper Lithology	8.5%	Low to Negligible	Interbedded and Slope	6%	Low to Negligible
10	CMI and Lower Lithology	6.6%	Low to Negligible	Source Depth and Vegetation Presence	8.5%	Low to Negligible	Upper Lithology Thickness and Slope	6%	Low to Negligible

Notes: Refer to Section 7 for description significance ranking and relative sensitivity.
CMI stands for Climate Moisture Index.

E-6.3 Additional Factors

Two additional factors were examined informally as part of the sensitivity analysis: slope-aspect; and, precipitation intensity. The first factor was the effect of ground surface slope-aspect on potential evapotranspiration rates. Slope angle is the angle that the ground surface makes with the horizontal, and aspect is the direction that a slope faces. The effect of increasing slope angle is to increase the solar radiation input and therefore increase potential evapotranspiration. For a 10 degree slope (18 %) an effect on the order of +/- 20% on potential evapotranspiration rates was calculated for a south or north facing slope, respectively. The effects of slope and aspect will be evaluated as part of the generic salt transport modeling and remediation criteria matrix development stage of this project study.

Between the two CMI boundary values considered in the sensitivity analysis, the range in the CMI between Whitecourt and Medicine Hat is 709 mm. An increase or decrease in potential evapotranspiration of 20% results in a variation in the CMI range of 13%. Therefore, the effect of a change in potential evapotranspiration on the CMI due to a change in aspect for a slope of 10 degrees is lower in magnitude when compared to the effect on CMI by considering diverse climate regions of Alberta.

For a variation of 13% in the CMI range, the net change in each response variable was calculated based on a linear interpolation between values for the Medicine Hat and Whitecourt CMI boundary values to gain further insight into the effect of slope on model sensitivity. The results are reported in the table below and are based on a simulation duration of 10 years.

Response Variables	Net Response Effect
Depth to peak chloride concentration	+/- 89 mm
Peak chloride concentration	+/- 44 mg/kg
Breakthrough depth for 250 mg/L	+/- 135 mm
Max. concentration in 0 to 1.5 m depth	+/- 45 mg/kg
Depth of max. concentration in 0 to 1.5 m depth	+/- 10 mm
Annual deep drainage	+/- 3 mm
Annual surface runoff	+/- 4 mm
Minimum annual water table depth	+/- 92 mm
Maximum annual water table depth	+/- 66 mm

For 10 years of chloride transport, the effects of a variation of 13% on the CMI are relatively low. If a linear extrapolation were used for a 100-year duration, the net response effects in the above table would increase by ten fold. Therefore the duration of chloride transport is a factor in determining the importance of slope and aspect on the net response. Adjustments for minor variation in CMI may be required as part of the matrix criteria development process and will be considered in the matrix development phase of the project to accommodate for the effects of slope and aspect.

The effect of precipitation intensity was not formally evaluated as part of the sensitivity analysis. However it was noted during preliminary modeling that for sandy soils with a free drainage boundary condition, the effect of rainfall intensity was noticeable on the downward transport of a chloride plume. For the sandy soils with a high drainage rate, a 1-day precipitation time series from the historical record produced a depth of penetration of the chloride peak to approximately 9 m after 10 years of simulation. For the same soil profile, a 7-day averaged rainfall rate produced a depth of peak chloride penetration to 6 m. This difference in penetration depths is significant. Although not tested, the difference in penetration depths for a fine-grained soil would be less. These results indicate that the effect of pulsed infiltration is an important mechanism of downward chloride transport in coarse-grained soil columns and this effect will be evaluated further during the generic criteria matrix development process based on calibrated model runs for different climate regions of Alberta.

E-7.0 Conclusions and Recommendations

Based on the results of the sensitivity analysis, the following conclusions and recommendations can be made:

1. the three highest factors for determining the depth of transport of the peak chloride concentration were: drainage boundary condition; source depth of the saline water release; and climate moisture index (CMI);
2. the four highest ranked factors for determining the magnitude of the peak chloride concentration were: CMI, longitudinal dispersivity, upper soil lithology texture, and vegetation presence;
3. the five highest ranked factors for breakthrough depth of 250 mg/L chloride concentration were: CMI, drainage boundary condition, source depth of the saline water release, upper soil lithology texture, and longitudinal dispersivity;
4. for model responses related to the water balance: deep drainage; surface runoff; and water table depth, the two highest ranked factors were drainage boundary condition and CMI;
5. significant interaction effects were observed between various factors such as drainage boundary condition, CMI, vegetation presence, and upper soil lithology texture due to combined effects on several response variables for soil water balance (*i.e.*, deep drainage, surface runoff, and water table depth) – certain interaction effects were significant and will require evaluation as part of the matrix criteria development process, however, in general their effect was smaller than the effect of high ranked individual factors;
6. in the free drainage scenario, a significant linear regression was established between the deep drainage rate of the soil column and the depth of transport of the chloride peak – greater drainage rates were associated with greater depths to peak chloride concentration highlighting the importance of this variable in the sensitivity analysis;
7. CMI is an important input factor in the salt transport model and thus generic matrix criteria should be developed separately for various regions of Alberta with different CMI values; and,
8. depth to the water table was identified as an important calibrating factor for the deep drainage rate, which was a high ranked factor in the sensitivity analysis - sites with characterization of seasonal water table depths would be of value in testing generic matrix criteria.

1 INTRODUCTION

This report details the methodology and results of a sensitivity analysis conducted by Equilibrium Environmental Inc. (Equilibrium) in support of the salt transport modeling portion of the Petroleum Technology Alliance Canada (PTAC) "*Project Study for the Development of Generic Site Assessment Criteria for Salinity below the Root Zone*". Saline water can be released to the environment as a result of oil and gas production activities and operation of road salt storage facilities. If saline water infiltrates into the soil, it may have negative effects on plant growth, shallow groundwater quality and soil hydraulic conductivity. Alberta Environment's site assessment criteria for soil salinity currently exist for the 0 to 1.5 m soil depth interval (topsoil and shallow subsoil). This depth interval is commonly referred to as the root zone. The PTAC project study was conceived with the ultimate goal of deriving generic site assessment criteria for salinity at depths below the root zone.

In order to reach this goal, a sensitivity analysis was conducted to better understand factors that influence salt transport in soil within and below the root zone. Those factors that are the most influential for determining salt transport will also be key determinants in the development of deep subsoil criteria. Salt transport modeling within the vadose (unsaturated) zone and shallow saturated zone was performed using public-domain computer software specifically designed for this purpose (*e.g.*, HYDRUS-1D and LEACHM).

A secondary aim of the sensitivity analysis completed in this PTAC study was to provide synergy with results from a previous sensitivity analysis completed by the American Petroleum Institute (API) (titled "*Modeling Study of Produced Water Releases*", 2005). The API sensitivity analysis evaluated the transport of salts from produced (saline) water releases towards a hypothetical drinking water well using a one-dimensional vertical salt transport model (HYDRUS-1D) coupled with a lateral groundwater transport model (MODFLOW and spreadsheet). Results of the API study identified variables that are primary determinants of potential increases in salt concentrations at a distant drinking water well due to a spill of produced water to shallow soil. The sensitivity analysis conducted for the PTAC project study focused on obtaining an improved understanding of salt transport within and below the shallow root zone and key determinants that lead to salinization of soils within the root zone. Thus the PTAC sensitivity analysis avoided duplication of the API study results.

A final product of this PTAC study will be a preliminary matrix of salinity criteria for generic assessment of saline impacts in soils below the root zone (*e.g.* below 1.5 m depth). Testing of the site assessment matrix criteria will be accomplished by conducting site-specific modeling for a number of saline-impacted sites located in diverse geographical areas of Alberta and Saskatchewan. Results from the sensitivity analysis reported herein will be used to guide the selection of sites for matrix testing and to identify site-specific variables that should be collected for modeling purposes.

The remainder of this document has been organized into the following sections:

1. Factor Selection (Section 2);
2. Response Variable Definition (Section 3);
3. Additional Parameter Definition (Section 4);
4. Methodology (Section 5);
5. Salt Transport Modeling (Section 6);
6. Sensitivity Analysis Results (Section 7); and
7. Conclusions and Recommendations (Section 8).

2 FACTOR SELECTION

Various input factors that have the potential to be key determinants in the transport of salts in soil and shallow groundwater were selected for examination in the sensitivity analysis. The factors selected encompassed a range of soil lithologies, climate conditions, produced water release scenarios, and plant cover conditions that represent diverse conditions in Alberta as well as western Canada. Eleven factors were selected and are shown in the table below. The absolute maximum and minimum of possible values for each factor were not selected as boundary values for the sensitivity analysis since they likely represent less probable combinations of site variables. Instead, high and low boundary values were based on reasonable values for Alberta to focus the sensitivity analysis on more probable combinations of site variables. The majority of sites with saline impacts are expected to fall within these boundary values.

Input Factor	Low Boundary Value	High Boundary Value
1. Climatic Moisture Index	-627 mm (Medicine Hat)	82 mm (Whitecourt)
2. Source Depth for Release	Surface	2 m
3. Upper Soil Lithology	Fine	Coarse
4. Lower Soil Lithology	Fine	Coarse
5. Upper Lithology Layer Thickness	2 m	4 m
6. Interbedding of Fine / Coarse Soils	None	Interbedded 0.5 m
7. Deep Drainage Boundary Condition	12 mm/year	Free Drainage
8. Vegetation Presence	None	Full Cover
9. Root Depth	0.5 m	1.5 m
10. Slope Induced Runoff	None	5% Slope
11. Longitudinal Dispersivity	100 mm	500 mm

A simulated soil column of 10 m thickness was selected and considered reasonably inclusive of typical unsaturated soil zone thicknesses at salt impacted sites in Alberta. From preliminary modeling results, the maximum penetration depth of the chloride peak in a uniform sandy loam soil under free drainage conditions was approximately 10 m within a 10 year period. Thus, a simulation duration of 10 years was selected.

Climate Moisture Index

The climate moisture index is a measure of the difference between annual precipitation and annual potential evapotranspiration. The formula for climate moisture index is:

$$CMI = P - PET$$

where,
P = average total annual precipitation (mm); and,
PET = average total annual potential evapotranspiration (mm).

Regions with a positive CMI are wetter and have a net surplus of precipitation annually available for infiltration into soil. Regions with a negative CMI are drier and the evaporative flux is generally high; although, it should be noted that total annual evapotranspiration is limited by the amount of available moisture. Therefore, actual annual evapotranspiration is not likely to reach the potential evapotranspiration rate. The CMI in Alberta ranges from approximately +150 mm (near Waterton) to -689 mm (northwest of Medicine Hat) (Agriculture and Agri-Food Canada

(AAFC), 1999). The wetter areas of the province occur near Swan Hills and in the upper Rocky Mountain Foothills. The drier areas occur in the southeast corner of the province near Medicine Hat.

The two boundary CMI values considered in the sensitivity analysis were taken from the Whitecourt climate station near the Swan Hills area and from the Medicine Hat climate station. The CMI for Whitecourt was calculated to be +82 mm, based on an average annual precipitation of 578 mm (taken from the Canadian Climate Normals Database; Environment Canada, 2000) and an average annual potential evapotranspiration of 496 mm (taken from the Canadian Ecodistrict Climate Normals Database; AAFC, 1999). The CMI for Medicine Hat was calculated to be -627 mm, with an average annual precipitation of 334 mm and an average annual potential evapotranspiration of 961 mm. These values are within the upper and lower bounds of the range of possible CMI values for Alberta (*i.e.*, +150 mm to -689 mm). Development of the precipitation time series for each site is discussed further in Section 4.

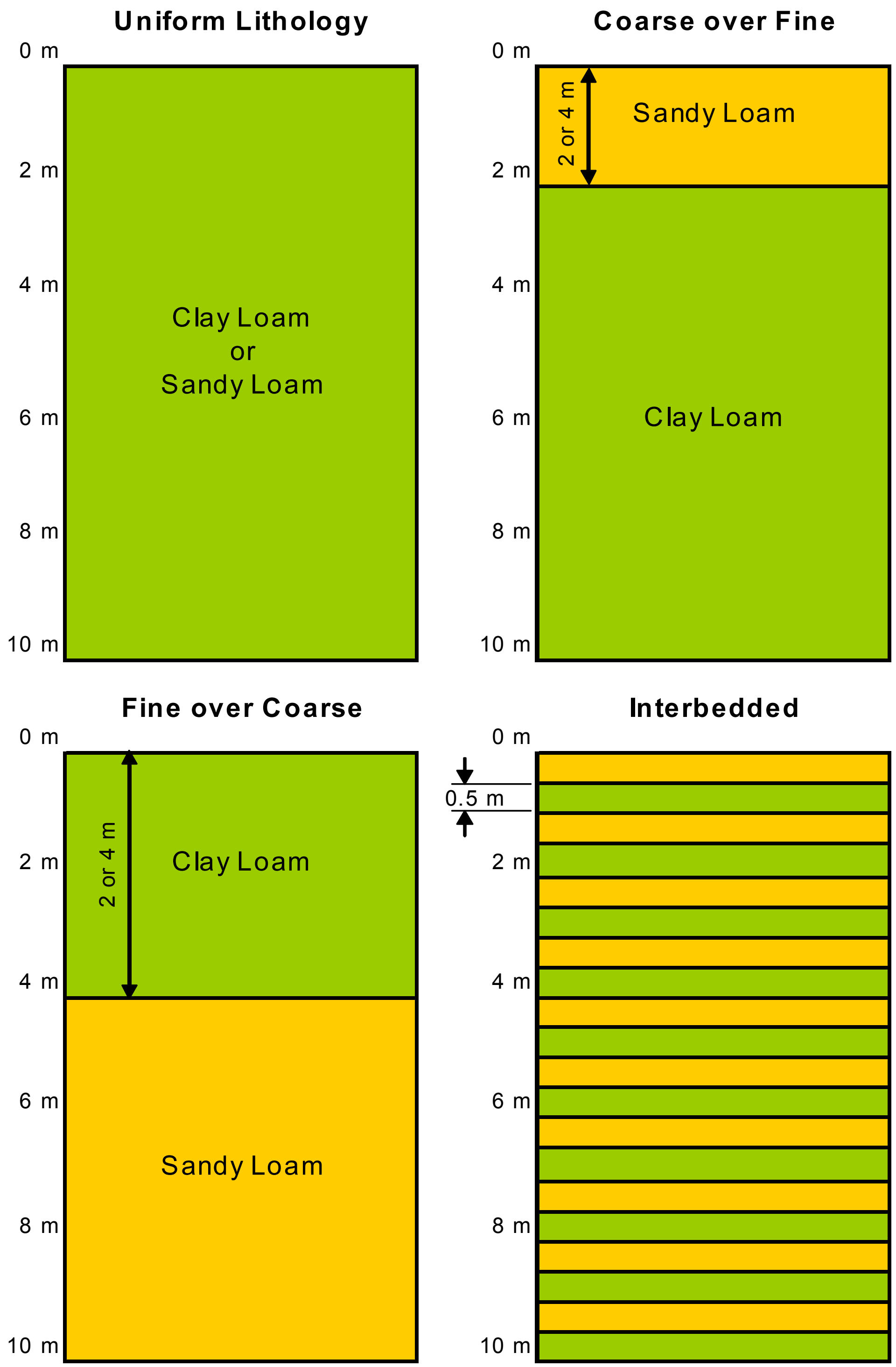
Source Depth for Release

The depth of the saline source of impact considered in the sensitivity analysis was determined based on experience with the release scenarios of interest outlined in the PTAC study scope of work (*i.e.*, pipeline breaks, flare pits, and salt storage facilities). A surface source and a source centered at 2 m depth (1.75 to 2.25 m) were selected. The surface source was considered representative of a salt storage facility source or a pipeline break source that has migrated to the soil surface. The 2 m depth source was considered representative of a flare pit base or a pipeline break at depth.

Upper and Lower Soil Lithology

The simulated soil column was divided into upper and lower sections to provide a means for investigating the effects of varying texture on salt transport. Soils were grouped into two general texture categories (*i.e.*, coarse and fine). Varying combinations of layering were considered, such as coarse over fine, fine over coarse, and uniform columns of fine or coarse soils. The reader is referred to Figure 1 for an illustration of the different soil lithology scenarios used in the sensitivity analysis modeling.

Reasonable boundary conditions were established to accommodate the majority of soil texture classifications at saline release sites while avoiding model instability caused by the layering of "extreme" differences in texture (*e.g.*, coarse well sorted gravel overlying swelling clay). Representative physical properties for each soil texture grouping were established from in-house and published literature datasets. Based on an analysis of the Agricultural Region of Alberta Soils Inventory Database (AGRASID; Alberta Agriculture Food and Rural Development (AAFRD), 2004), 23,396 records exist in the database for mineral (non-organic) soils. Sandy loam soils were reported for 2,158 records compared to 487 records for loamy sand and 212 records for sand (all of these textures were considered coarse). For the three coarse textured soils 76% (2,158 out of 2,857) were sandy loam soils. For finer grained soils, clay loam was reported for 4,701 records with 492 records for clay and 226 records for heavy clay. For these three fine textured soils 87% (4,701 out of 5,419) were clay loam soils. Therefore the two boundary values selected for the coarse and fine texture soil categories were sandy loam and clay loam soils, respectively. These conditions were considered representative of the majority of soil texture groupings expected to be present at saline impacted sites. It should be noted that textures considered "outside of these boundary values", in terms of the magnitude of influence on salt transport as a result of their physical properties, will be considered in the criteria matrix



PTAC	**EQUILIBRIUM ENVIRONMENTAL**	
Figure 1. Soil Lithology Combinations For Sensitivity Analysis	**09/18/2005**	**Sensitivity Analysis**
	Drawn by: MVC	**Job#: OW-15**

development process as special cases. Examples of special cases would include: muskeg soils, swelling clays, and gravel.

Upper and Lower Soil Lithology Layer Thickness

Two upper soil lithology layer thicknesses were considered to evaluate the effect of general types of texture layering that could be expected at saline impacted sites. These thicknesses were 2 or 4 m of coarse or fine soil overlying the lower soil lithology layer. The thickness of the lower soil layer was the difference between 10 m (maximum soil depth considered in the model) and the upper soil layer thickness.

Interbedding of Fine and Coarse Soils

The importance of relatively thin interbedded layers of fine and coarse soils on the net bulk transport of salts was examined. The thickness of each interbedded layer was assumed to be 0.5 m (see Figure 1). The sensitivity of the model output to the presence, or absence, of an interbedded soil texture column was established by comparing the model results against a soil column without interbedding.

Drainage Boundary Condition

The drainage boundary condition is defined as the net downward rate of water flux that exits the base of the modeled soil column where a domestic useable aquifer (DUA) was hypothetically assumed to be located. This condition controls the depth of the water table, and thus the thickness of the saturated zone, for a given soil column. Situations with a high drainage rate leads to a deeper water table and relatively thin saturated zone. Situations with a low drainage rate leads to a shallower water table and thick saturated zone. Two drainage rates were considered: a low drainage rate of 12 mm/yr considered representative of a fine soil layer overlying a DUA, the reported drainage rate for clay till in Alberta (Alberta Environment, 2001); and, a high or “free” drainage rate considered representative of a situation where a deeper and relatively low permeability layer is assumed to not be present between the depth of saline impacted soils and the water table. The free drainage rate varied between model runs (*i.e.*, rates ranged from 6 mm/yr to 190 mm/yr) since it was controlled by multiple variables (*e.g.*, net moisture infiltration, the presence of plants, soil texture and associated drainage in the saturated zone of the modeled soil column, *etc.*). Results from this component of the sensitivity analysis were also used to develop a relationship between peak chloride transport depth and drainage rate at the lower boundary of the modeled soil column (discussed in Section 7).

Vegetation Presence and Root Depth

The vegetation presence factor is an important variable that in part determines the role of water balance in topsoil and shallow subsoil (0 to 1.5 m depth) on the net transport of salts. The root system of the plants provides a mechanism of water removal from the soil column throughout the root zone by the process of transpiration. Situations where plant growth is absent lead to water removal from the soil column solely through the process of evaporation at the soil surface. Two root depths were also considered (0.5 and 1.5 m). These depths were assumed to be representative of the typical maximum root depth of agricultural plants and native plant species found in various ecoregions of Alberta (*e.g.*, boreal forest, grasslands). The two boundary values simulated for vegetation presence were 100% and zero plant cover.

Slope Induced Runoff

The effect of ground slope on generating runoff from available precipitation was investigated to determine the magnitude of influence of this factor on net salt transport. Ground slope can affect salt transport by reducing the amount of water that infiltrates into the soil column. Boundary conditions of 0 and 5% slope were selected. A 5% slope was considered to be a reasonable upper limit for the variability of ground slopes at salt impacted sites as well as a defining point below which vertical transport is likely to be the predominant vector. For steeper slopes, it can be expected that horizontal transport would be a significant vector, which would complicate the interpretation of results from a sensitivity analysis focused on vertical salt transport.

Longitudinal Dispersivity

Dispersion is the process of mechanical spreading of the center of solute mass due to tortuosity of the soil pore space causing variations in the flow velocity. Not all flow paths through soil pores are of equal length or size. These differences in flow velocity cause spreading of the center of solute mass. Longitudinal (in the direction of groundwater flow) dispersivity is used to represent the effect of variations in groundwater flow velocity on solute concentration according to the equation:

$$\alpha = \frac{D}{v}$$

where,
α = longitudinal dispersivity;
D = longitudinal dispersion coefficient; and,
v = average pore water velocity.

Longitudinal dispersivity has been shown to increase with increasing scale of the transport medium. In other words, for longer contaminant transport distances a larger longitudinal dispersivity coefficient should be used. Regression equations produced by Schultze-Makuch (2005) were used to gain an estimate of the upper and lower limits on the range of expected longitudinal dispersivity values. Using a lower estimate for transport length of 1 m and an upper estimate for transport length of 10 m, longitudinal dispersivities of 130 and 550 mm were calculated. From these calculated results, a lower longitudinal dispersivity limit of 100 mm and an upper limit of 500 mm were selected for use in the sensitivity analysis.

3 RESPONSE VARIABLE DEFINITION

Nine model response variables were selected to provide measures against which the sensitivity of the model could be assessed. The response variables, grouped into two categories (chloride transport and water balance), included:

Model response variables related to chloride transport
- depth to peak soil chloride concentration;
- peak magnitude of soil chloride concentration;
- breakthrough depth of 250 mg/L soilwater chloride concentration;
- maximum soil chloride concentration in the 0 to 1.5 m depth interval;
- depth of maximum soil chloride concentration in the 0 to 1.5 m depth interval;

Model response variables related to water balance

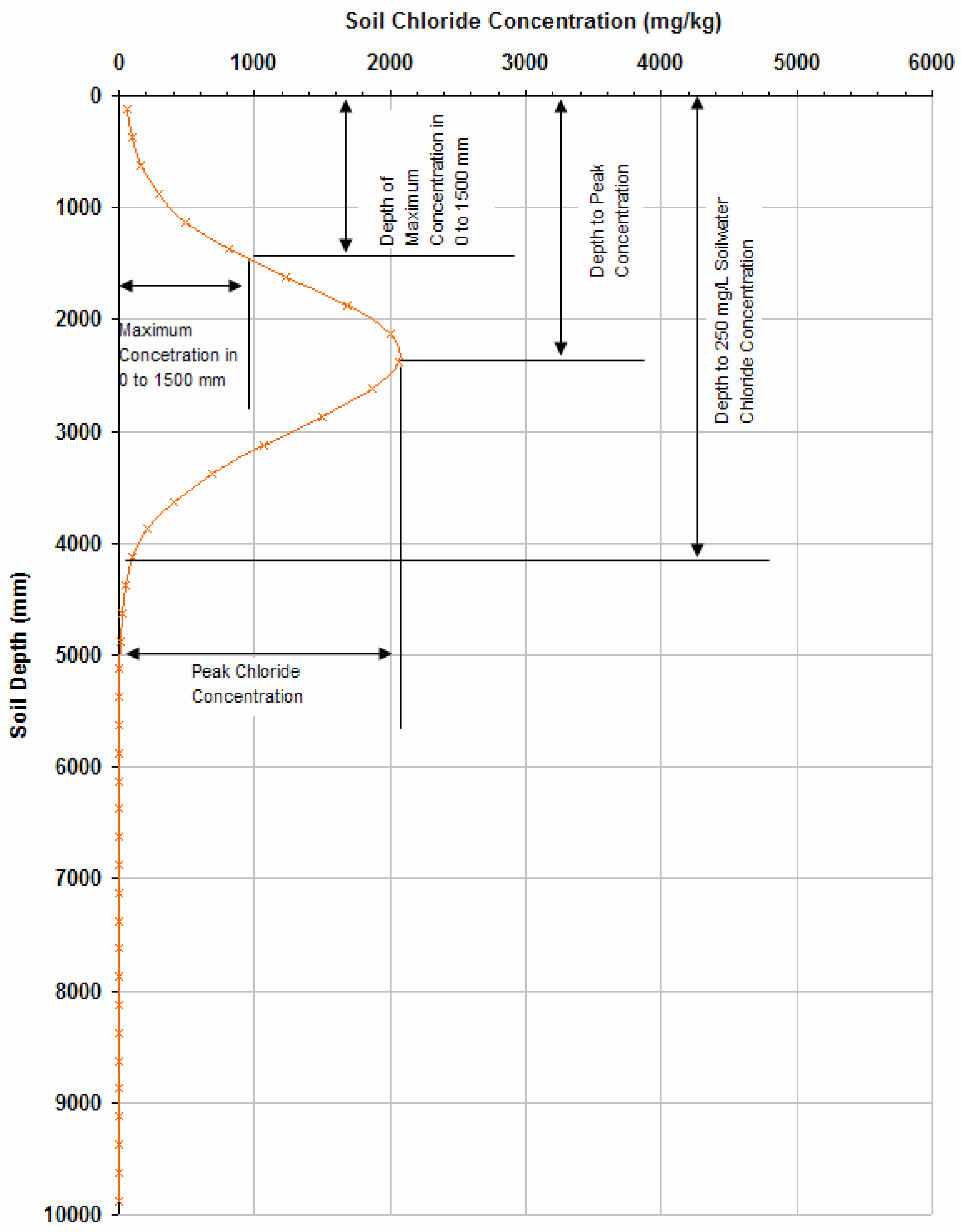
- annual deep drainage of the soil column;
- annual surface runoff;
- maximum annual water table depth; and,
- minimum annual water table depth.

Figure 2 graphically defines the five response variables related to chloride transport based on a hypothetical vertical chloride profile within a modeled soil column. The peak soil chloride concentration provides a measure of the degree of attenuation of the peak concentration for a 10-year simulation. The depth of the peak soil chloride concentration is a measure of the vertical transport rate of the plume over 10 years. The breakthrough depth of 250 mg/L soil water chloride concentration provides a measure of the vertical depth of penetration of the plume in units that are compatible with the aesthetic drinking water objective for chloride in Alberta. The maximum soil chloride concentration in topsoil and shallow subsoil (0 to 0.3 and 0.3 to 1.5 m) provides a measure of the degree to which chloride ions are transported into the rooting zone. The variables related to water balance refer to the net annual water balance of the soil column being simulated. As will be shown in the discussion of results (Section 7), the net vertical movement of water (and thus net annual water balance) is highly correlated with the net vertical transport of chloride. The maximum and minimum water table depth variables are useful in that they provide results that can be compared with typical field investigation results (*i.e.*, groundwater elevations) at salt impacted sites, which provides context and a tangible endpoint for assessing the field relevance of the sensitivity analysis results.

4 ADDITIONAL PARAMETER DEFINITION

Precipitation Time Series

The CMI was previously defined in Section 2 and is based on an annual value for the net of precipitation and potential evapotranspiration. The precipitation component of the CMI is comprised of rainfall and snowfall events, which vary in frequency and intensity throughout a given year and between years. A precipitation time series was generated by selecting an average year for total precipitation and utilizing the daily precipitation record for that year from the Canadian Climate Data CD (Environment Canada, 2002). Infiltration events for input into the salt transport model were developed by separating the daily precipitation into a rainfall and snowmelt time series. This was accomplished using the snowmelt routine in HYDRUS-1D (Simunek et al., 2005). The snowmelt routine assigns precipitation events as rainfall if the air temperature is above +2 ºC, and assigns precipitation as snowfall if the air temperature is below -2 ºC. There is a linear transition between rainfall and snowfall between these two temperature limits. Snowfall is accumulated by the model during winter months and produces snowmelt as water available for infiltration on days when the air temperature rises above 0ºC. A user-specified melting constant is then applied. This procedure produced an approximately realistic behaviour of rainfall-snowmelt processes. Potential evapotranspiration rates in the Ecodistrict Climate Normals Database are reported as monthly totals (AAFC, 1999). These totals were converted into either a daily or weekly evapotranspiration rate for input into either the HYDRUS-1D or LEACHM transport models respectively.



PTAC	**Equilibrium Environmental**	
Figure 2. Definition of Chloride Modeling - Measured Response Variables	09/20/2005	Sensitivity Analysis
	Drawn by: MVC	Job#: PT-02

Soil Physical Properties

A number of soil parameters were required to define the hydraulic and moisture retention characteristics for the sandy loam and clay loam soils. Equilibrium's in-house database of soil properties contained 21 clay loam samples for Alberta soils. The Equilibrium database for sandy loam soils was smaller with only two samples. Therefore the sandy loam database was augmented with data from the Unsaturated Soils Database (UNSODA) from the United States Salinity Laboratory (United States Department of Agriculture (USDA), 1999). A total of 53 samples were used to calculate the saturated hydraulic conductivity (*Ksat*) for the sandy loam. The soil parameters used in the salt transport modeling are contained in the table below.

Soil Type	**Bulk Density (g/cm^3)**	**Ksat (mm/d)**	**Porosity**	**Moisture Retention Parameters***	
				α (kPa)	**β**
Sandy Loam	1.685	422	0.357	0.658	9.07
Clay Loam	1.620	0.79	0.381	2.66	15.5

*Note: Moisture retention parameters correspond to those of Campbell (1974).

The moisture retention parameters were produced by regression fitting to measured data from the UNSODA and Equilibrium databases using the RETC program (USDA, 1998) and MS-Excel.

5 METHODOLOGY

The method of sensitivity analysis selected for use in this PTAC study was based upon a "design of experiments" (DEX) methodology using factorial analysis. A two-value full factorial analyses involves a series of experiments (in this case model runs) where the value of each factor is varied between boundary values. Factorial analysis uses a single change in a single factor for each model run. For a large number of factors, this can lead to a large number of required runs, since the total number of runs required is 2^k, where k is the number of factors being tested. The number of factors tested for this study was 11, which would result in a required number of runs of 2048. Fractional factorial analysis reduces the number of required model runs by varying more than one factor at a time in the same run. The fractional factorial design selected for this sensitivity analysis was a $2_V^{(11-4)}$ design. The design notation indicates the resolution of the design "*V*" (roman numeral) and the extent of fractionation (*11-4=7*). In other words, the fraction of runs required is 2^7 or 128 runs as compared to 1048 runs for a full factorial analysis. This design is a resolution V design, which means that it is capable of maintaining resolution of 4th order interaction effects. The order of interaction is one less than the number of factors interacting. For example, first order interaction effects are the cause of two factors interacting to produce an effect on model results. A resolution V design was considered sufficient to maintain resolution of any significant interaction effects that may occur between the 11 factors.

For data analysis purposes, each factor is assigned a low (-1) and a high (+1) boundary value in a matrix of scenario runs. The run matrix for the $2_V^{(11-4)}$ design was taken from the National Institute of Standards and Technology (NIST) Engineering Statistics Handbook (NIST, 2005). The run matrix is included in Appendix A, Table A-1 of this report. The run matrix determines the boundary value (-1 or +1) for each factor in each of the 128 runs, for which the results are presented in Section 7.

6 SALT TRANSPORT MODELING

Salt transport modeling for the sensitivity analysis was conducted using public-domain software packages. The models used in this study were HYDRUS-1D and LEACHM. Both packages solve the one-dimensional form of Richard's Equation for unsaturated water flow in soil and the convection dispersion equation (CDE) for chemical transport. The water flow and transport equations solved are the same for the two programs; however, the programs vary in the method of numerical solution, spatial discretization, and numerical subroutines. In particular two subroutines unique between the two programs were used in the salt transport modeling. A snowmelt routine is implemented within HYDRUS-1D that allows simulation of snow accumulation during cold periods and melting of accumulated snow during warmer periods. While LEACHM does not implement a snowmelt routine, it has a slope-runoff routine that is unique from HYDRUS-1D. The slope-runoff routine incorporates a surface slope calculation that apportions more rainfall to runoff on steeper slopes.

LEACHM simulations required substantially less time to attain a full ten year simulation, due primarily to model instability encountered when using HYDRUS-1D. The large variation in input factors (*e.g.* daily rainfall intensity) produced frequent instabilities in the HYDRUS-1D model and increased time and effort accordingly. During an evaluation of the HYDRUS program by the United States Geological Survey (USGS, 2005), time-consuming convergence problems were noted in association with heavy rainfall events. Therefore an advantage of LEACHM, in terms of efficiency, included the production of readily available results that were suited to batch runs (running many simulations in series). As a result of these issues, LEACHM was used for the chloride transport component of the sensitivity analysis.

The snowmelt routine in HYDRUS-1D was used to produce time series of infiltration events given daily rainfall, snowfall, and temperature for Whitecourt and Medicine Hat. The HYDRUS-1D infiltration time series was subsequently incorporated into the LEACHM simulations. It is envisioned that HYDRUS-1D will be used more extensively during the site assessment criteria matrix testing stage of the PTAC project study due to its ability to model clay dispersion effects as a result of elevated sodium to calcium plus magnesium ratios (*i.e.*, effects related to the sodium adsorption ratio (SAR) parameter). Any allowances in data input required to improve the stability of the HYDRUS runs (*e.g.* smoothed precipitation time series) will be addressed during the matrix criteria development stage of this project.

The salt transport modeling performed for the sensitivity analysis involved a simple one-time release of a mass of chloride-rich water. The input mass of chloride was selected to be 600 mg/cm^2, which corresponds to an approximate solution concentration of 30,000 to 35,000 mg/L (depending on soil porosity) applied to a vertical soil layer thickness of 0.5 m. The chloride-rich water was applied at the start of the model simulation at the two source depth intervals defined in Section 2 (*i.e.*, 0 to 0.5 m and 1.75 to 2.25 m).

For each of the 128 simulation runs, a preliminary water balance run of 20 years was conducted to attain a stable annual water balance in the soil column. The moisture content profile from the water balance run was then used as input into the 10-year salt transport runs. The criterion for a stable water balance was a maximum difference of 1% between years 19 and 20. All of the water balance runs met this criterion. A criterion of 1% difference in the chloride mass balance between zero 0 and year 10 in the salt transport runs was used to ensure mass conservation in the model.

The annual water balance equation for the one-dimensional soil column is as follows:

$$P - ET - U = R$$

where,

P = annual precipitation;
ET = evapotranspiration from plants and the soil surface;
U = surface runoff; and,
R = deep drainage from the base of the soil column.

(Notation taken from CCME guidelines, 1996)

The annual water balance assumes no net change in water storage (*e.g.* a dynamically stable water table). The above equation was solved on a daily time interval using the transport model. The sensitivity of deep drainage, surface runoff and water table depth were analyzed. Water producing surface runoff was assumed to be removed from the system (such as via surface drainage), and thus water was not allowed to pond on the soil surface. Surface runoff is generated when the infiltration capacity of the soil is exceeded. This generally occurs during periods of high intensity or prolonged periods of rainfall, when the upper soil column becomes saturated. Runoff is produced by soil saturation and the inability of the upper soil to conduct water to depth.

7 SENSITIVITY ANALYSIS RESULTS

For each of the 128 sensitivity analysis model runs, measured response variable (defined in Section 3) results were extracted and are contained in table format in Appendix A, Table A-2. The analysis of the model responses (*e.g.* depth to peak chloride concentration) was based on examining the difference between the average (mean) response for the high and low boundary values for a given factor. For the majority of measured responses, there were 64 runs completed at each of the high and low boundary values for the 11 input factors (*e.g.* climate moisture index, source depth, *etc*.). The sensitivity of a response variable to an input factor was taken to be the mean of the differences in response for the high and low factor boundary values. Details of the results analysis is explained further in subsequent sections.

Significance testing by pooled t-test was conducted on calculated sensitivities to determine the statistical level of significance of the results. Significance testing allows for the determination of what level of sensitivity is considered to be sufficiently greater than zero to be important. The significance ranking used in this report is summarized below:

- Highly sensitive input factors were assigned a significance level of 5%;
- Moderately sensitive input factors were assigned a significance level of 10%; and,
- Low or negligibly sensitive input factors were classified as such if they were not significant at the 10% level.

A relative sensitivity was developed by assigning a value of 100% to the most sensitive main effect. The relative sensitivity for subsequent effects was calculated as a percentage of the most sensitive effect.

7.1 MAIN EFFECTS

Main sensitivity effects are defined as the effect of a single input factor (*e.g.* climate index) on a response variable (*e.g.* depth to peak chloride concentration). The main effects for each of the

11 input factors were calculated from the mean effect (the mean of the difference in response for the high and low factor boundary values). The results are presented in mean effects plots (Figures 3 to 7) for each of the measured response variables. The magnitude of the range of each line plotted on the mean effects chart indicates the sensitivity of the response to that factor. Thus, larger response magnitudes are associated with greater model sensitivities to the various factors. The sensitivity rankings for each factor and each response variable are summarized in Table 1 below. Detailed response values for the rankings are contained in table format in Appendix A, Table A-3.

7.1.1 Model Response Variables Related to Chloride Transport

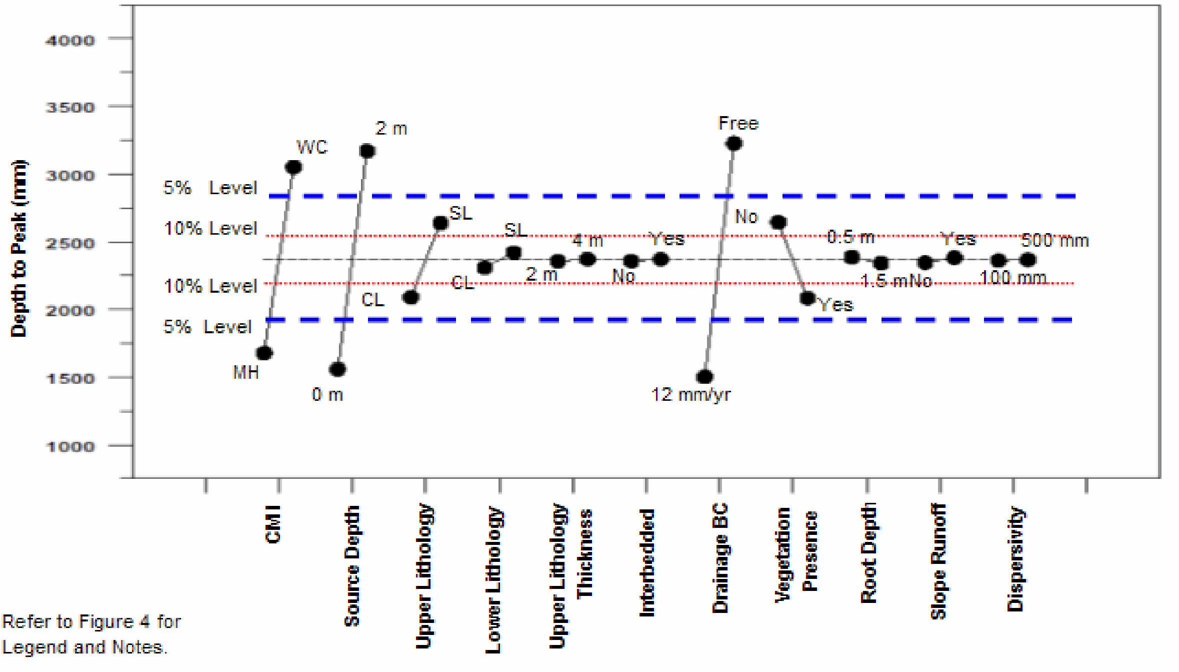
Three measures of the depth of chloride transport were included to give an approximate description of the shape of the plume as it developed after release. The response variables measuring depth of chloride transport were: the depth to the peak chloride concentration; the breakthrough depth of 250 mg/L chloride concentration; and, the depth to the maximum chloride concentration in the 0 to 1.5 m depth interval. The top three factors to which all of these model responses were the most sensitive were: 1) climate moisture index (CMI), 2) source depth; and 3) drainage boundary condition, in varying order. These factors produced responses that were considered significant at the 5% level. Source depth is logically related to the location of the chloride depth profile. The other two factors are related to the water balance in the soil column. The CMI is an approximate measure of the total available water for infiltration, whereas the drainage boundary condition essentially controls the rate at which water can leave the base of the soil column. The magnitude of the CMI is analogous to the degree to which a tap is turned on allowing water to flow through a pipe, whereas the magnitude of drainage at the bottom boundary is analogous to a valve controlling the flow of water out of the pipe. The next highest ranked factors were: vegetation presence, upper lithology texture, and longitudinal dispersivity.

Two measures of chloride concentration were included in the sensitivity analysis. The response variables used were: the magnitude of peak chloride concentration; and, the maximum chloride concentration in the 0 to 1.5 m depth interval. The top five factors to which the peak chloride concentration was most sensitive were: 1) moisture index; 2) longitudinal dispersivity; 3) upper soil lithology texture; 4) vegetation presence; and, 5) source depth. The top four of these factors had a significant effect at the 5% level and the fifth at the 10% level. Generally, a greater rate of moisture movement in the soil column (due to moisture availability or hydraulic conductivity) is associated with greater attenuation of the peak concentration. The effect of the longitudinal dispersivity on model sensitivity was of similar magnitude as the CMI and resulted in a wider peak, based on results for breakthrough depth of the 250 mg/L soil water concentration.

7.1.2 Model Response Variables Related to Water Balance

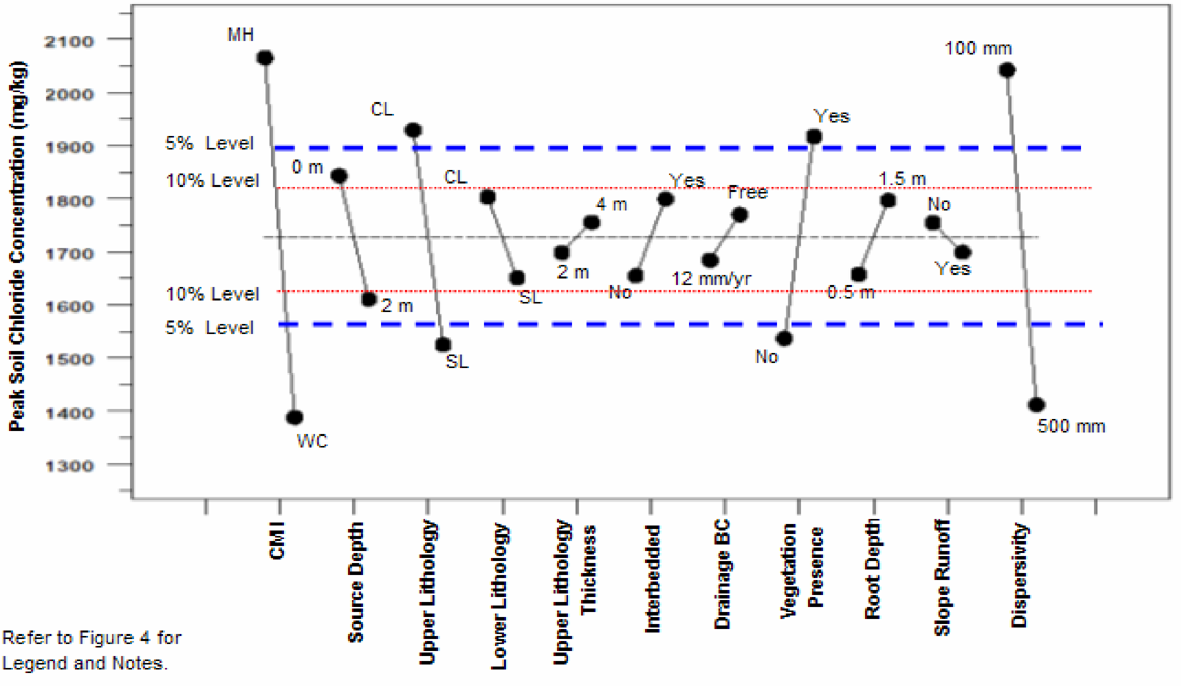
Four model response variables were examined with regards to the soil column water balance. The responses were: annual deep drainage; annual surface runoff; minimum annual water table depth; and annual maximum water table depth. The magnitude of deep drainage was most sensitive to: 1) drainage boundary condition; 2) CMI; 3) vegetation presence; and, 4) upper soil lithology. The first three factors were significant at the 5% level and the fourth at the 10% level. The effect of the deep drainage boundary condition on the net water balance is logical since it controls the rate by which water exits the base of the soil column. The free drainage factor produced a range of drainage rates. Drainage rate was plotted against depth to peak chloride concentration to determine whether a relationship exists between this factor and response variable combination in Figure 8. Results from 128 simulations are included in this figure. The data were separated into two subsets representing initial source depths of 0 and 2 m.

Depth to Peak Chloride Concentration After 10 Year Simulation Duration



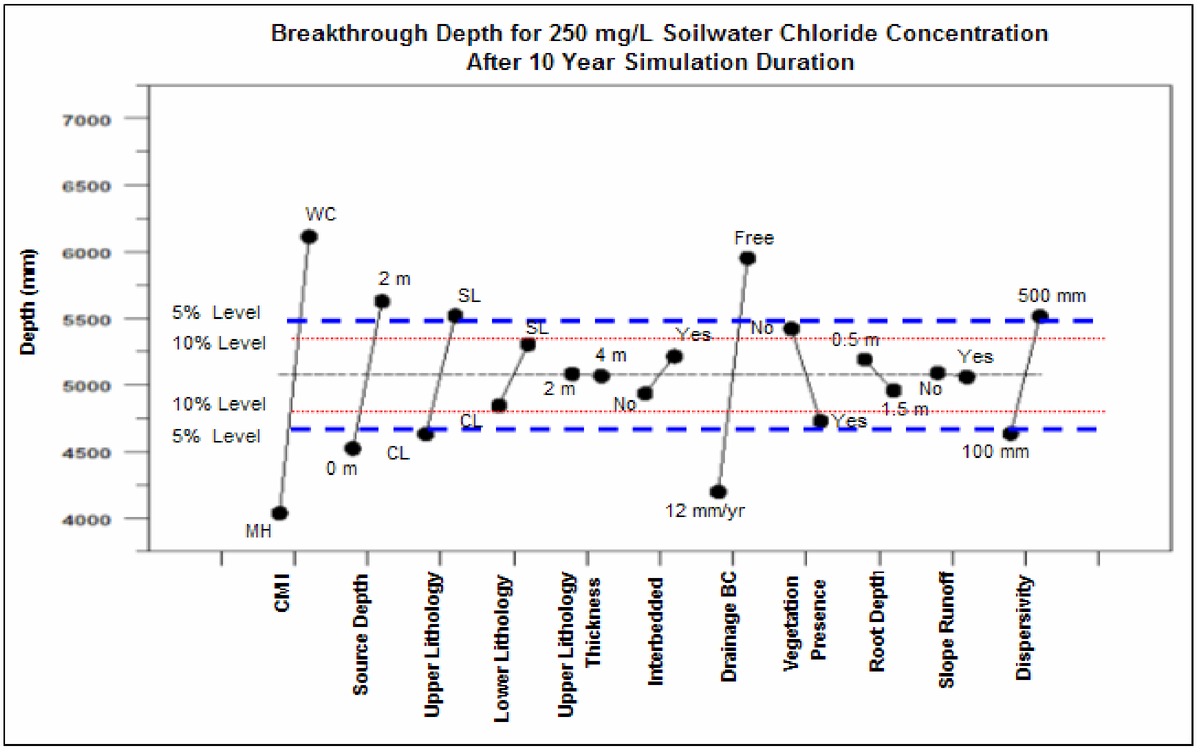
Refer to Figure 4 for Legend and Notes.

Peak Chloride Concentration After 10 Year Simulation Duration



Refer to Figure 4 for Legend and Notes.

PTAC	EQUILIBRIUM ENVIRONMENTAL	
Figure 3. Mean Effects Plots Depth to Peak and Peak Concentration	09/15/2005	Sensitivity Analysis
	Drawn by: MVC	Job#: PT-02



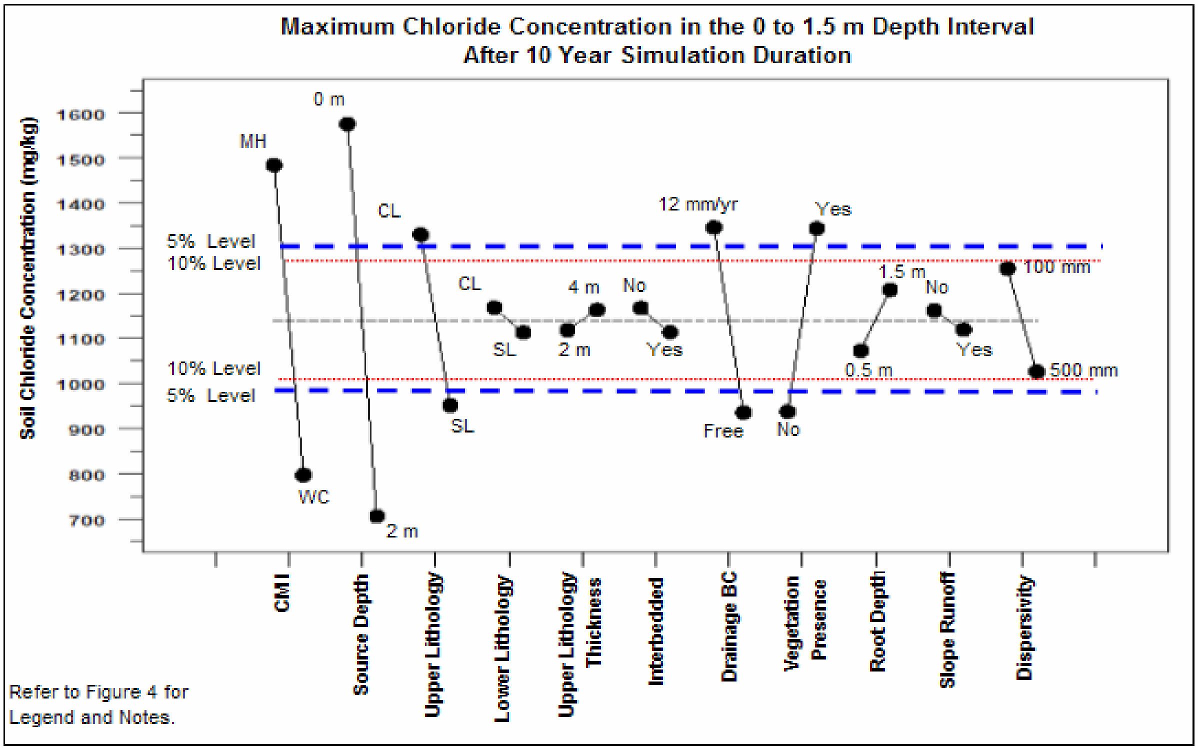
LEGEND:

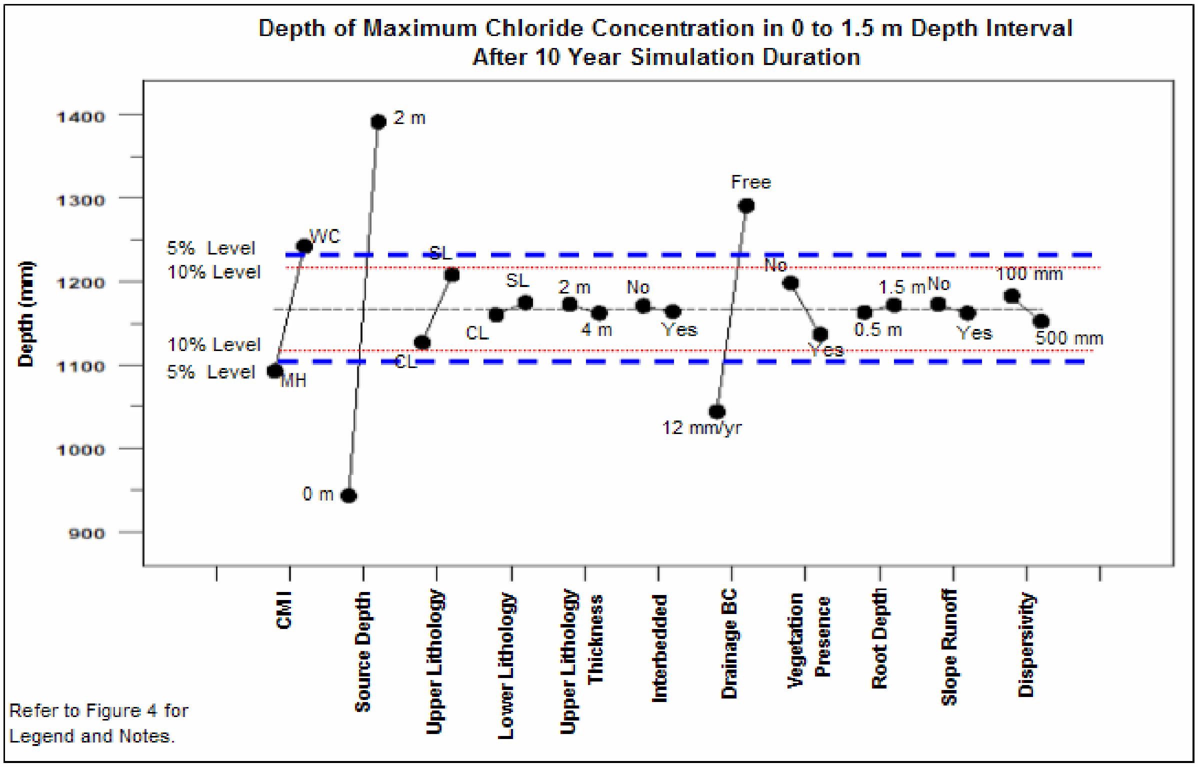
– – –	Upper and lower bounds for 5% statistical significance level (approximate).
·········	Upper and lower bounds for 10% statistical significance level (approximate).
- - - - - -	Global mean value for all model runs.
●	Data point represents the mean value for all model runs at either the high or low factor setting.

NOTES:

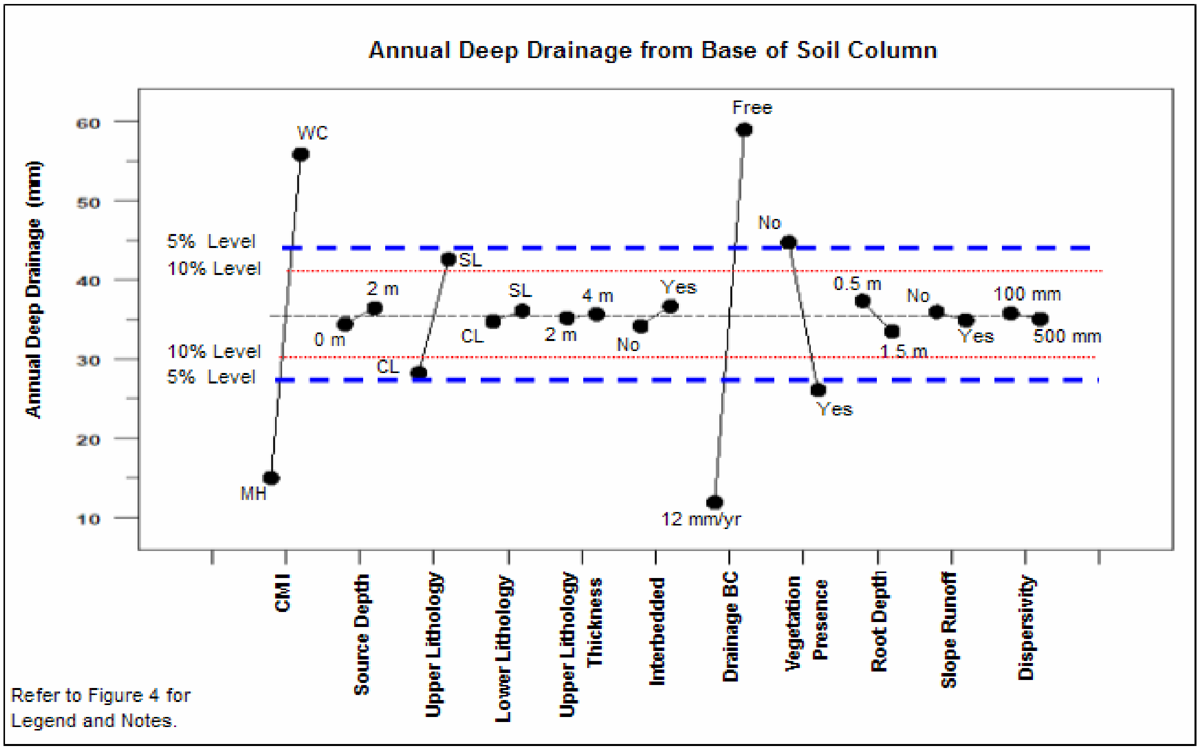
1. Data points lying above or below dashed blue line are considered statistically significant at the 5% level.
2. For water table depth results (Figure 7), only the runs for the 12 mm/yr drainage boundary condition were included. The free drainage boundary condition runs had water table depths > 10 m and therefore were not recorded.
3. "SL" and "CL" labels for soil lithology refer to Sandy Loam and Clay Loam soils respectively.
4. "MH" and "WC" labels for Climate Moisture Index (CMI) refer to Medicine Hat and Whitecourt climate data respectively.

PTAC	**EQUILIBRIUM ENVIRONMENTAL**	
Figure 4. Mean Effects Plot Breakthrough Depth for 250 mg/L Concentration	**09/15/2005**	**Sensitivity Analysis**
	Drawn by: MVC	**Job#: PT-02**

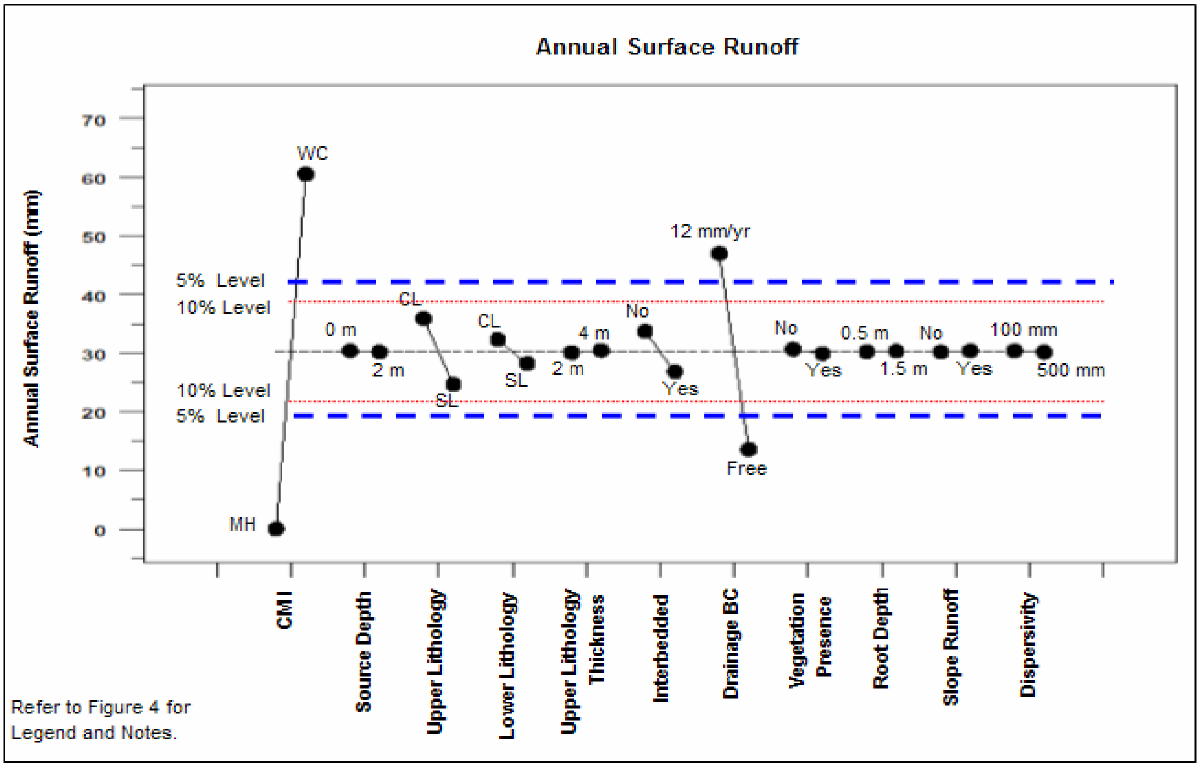




PTAC	EQUILIBRIUM ENVIRONMENTAL	
Figure 5. Mean Effects Plots Maximum Concentration in 0 to 1.5 m Depth Interval	09/15/2005	Sensitivity Analysis
	Drawn by: MVC	Job#: PT-02

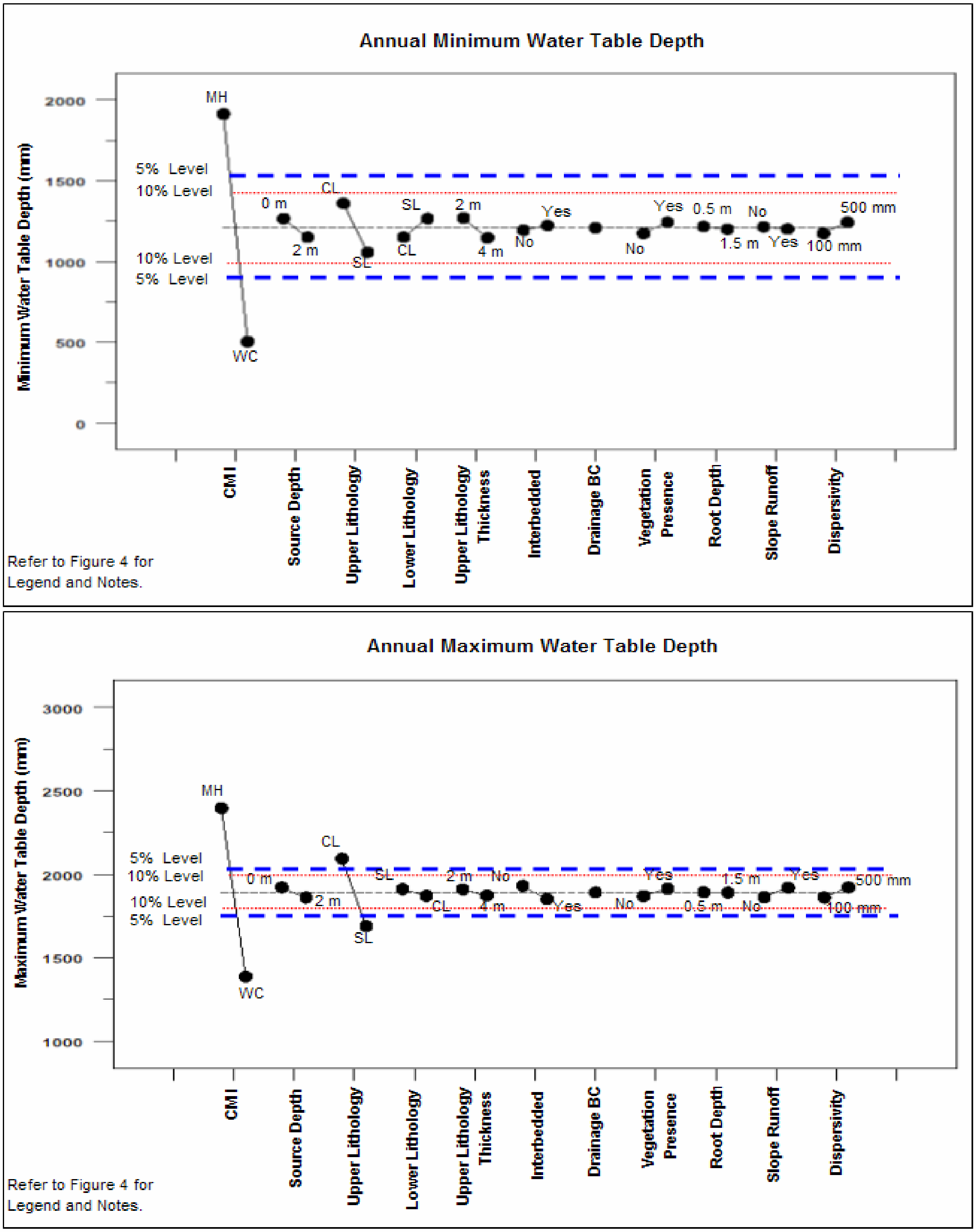


Refer to Figure 4 for
Legend and Notes.



Refer to Figure 4 for
Legend and Notes.

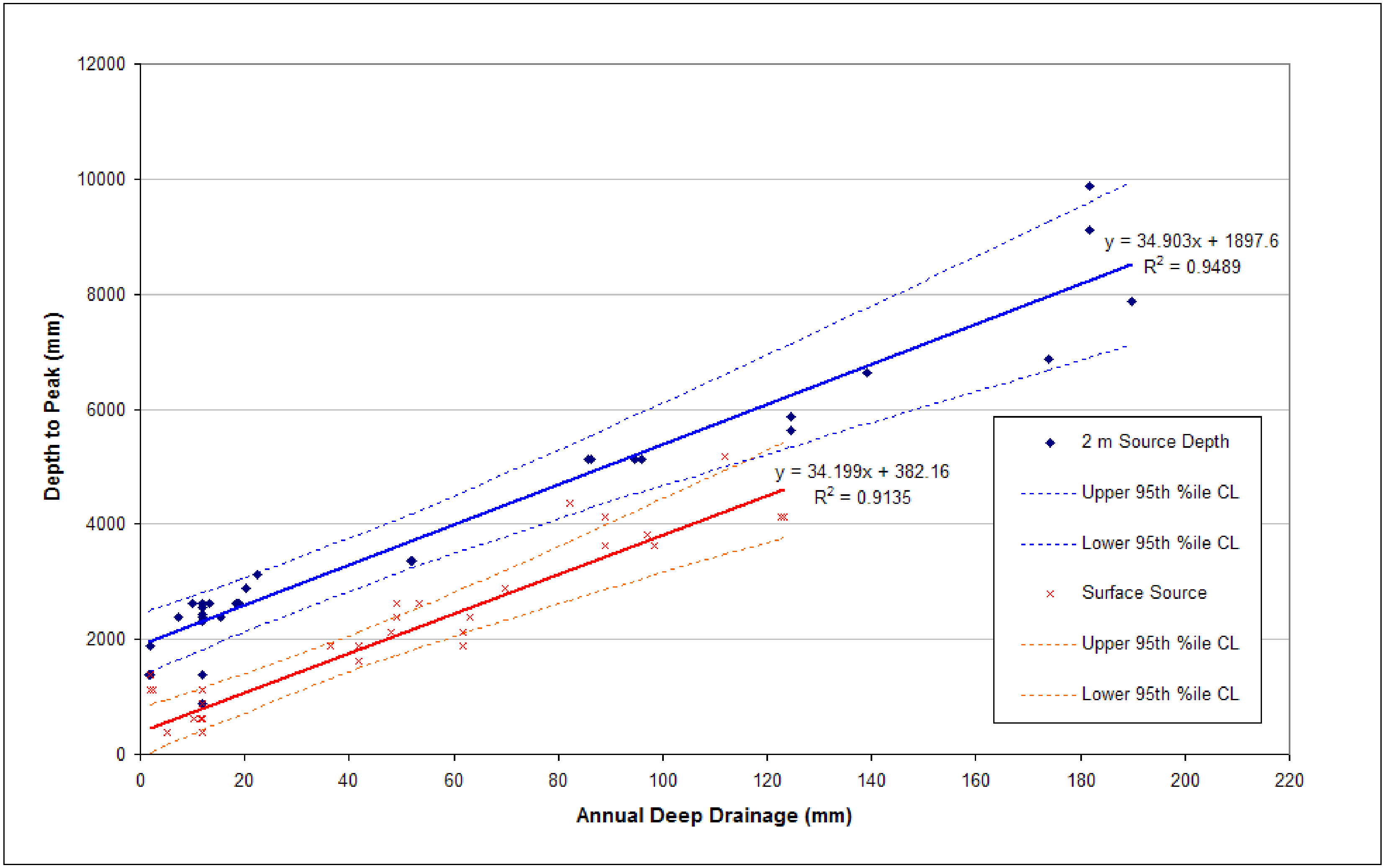
PTAC	EQUILIBRIUM ENVIRONMENTAL	
Figure 6. Mean Effects Plots Deep Drainage and Surface Runoff	09/15/2005	Sensitivity Analysis
	Drawn by: MVC	Job#: PT-02



Refer to Figure 4 for Legend and Notes.

Refer to Figure 4 for Legend and Notes.

PTAC	EQUILIBRIUM ENVIRONMENTAL	
Figure 7. Mean Effects Plots Minimum and Maximum Water Table Depths	09/15/2005	Sensitivity Analysis
	Drawn by: MVC	Job#: PT-02



PTAC	**EQUILIBRIUM ENVIRONMENTAL**	
Figure 8. Deep Drainage versus Depth to Peak Chloride Concentration	**09/15/2005**	**Sensitivity Analysis**
	Drawn by: MVC	**Job#: PT-02**

Table 1. Main Effects Sensitivity Rankings for Model Responses

Ranking	Depth to Peak			Peak Concentration			Breakthrough Depth for 250 mg/L Concentration		
	Factor	**Relative Sensitivity**	**Significance Ranking**	**Factor**	**Relative Sensitivity**	**Significance Ranking**	**Factor**	**Relative Sensitivity**	**Significance Ranking**
1	Drainage BC	100%	High	CMI	100%	High	CMI	100%	High
2	Source Depth	93%	High	Dispersivity	95%	High	Drainage BC	85%	High
3	CMI	80%	High	Upper Lithology	59%	High	Source Depth	53%	High
4	Vegetation Presence	32%	Moderate	Vegetation Presence	57%	High	Upper Lithology	43%	High
5	Upper Lithology	32%	Moderate	Source Depth	35%	Moderate	Dispersivity	42%	High
6	Lower Lithology	6.4%	Low to Negligible	Lower Lithology	23%	Low to Negligible	Vegetation Presence	33%	Moderate
7	Root Depth	2.5%	Low to Negligible	Interbedded	21%	Low to Negligible	Lower Lithology	22%	Low to Negligible
8	Slope Runoff	2.2%	Low to Negligible	Root Depth	20%	Low to Negligible	Interbedded	13%	Low to Negligible
9	Upper Lithology Thickness	0.9%	Low to Negligible	Drainage BC	14%	Low to Negligible	Root Depth	11%	Low to Negligible
10	Interbedded	0.9%	Low to Negligible	Upper Lithology Thickness	8.6%	Low to Negligible	Slope Runoff	1.4%	Low to Negligible
11	Dispersivity	0.4%	Low to Negligible	Slope Runoff	8.2%	Low to Negligible	Upper Lithology Thickness	0.7%	Low to Negligible

Notes: Refer to Section 7 for description significance ranking and relative sensitivity.
CMI stands for Climate Moisture Index.

Table 1 Cont'd. Main Effects Sensitivity Rankings for Model Responses

Ranking	Maximum Concentration 0 to 1.5 m			Depth of Maximum Concentration 0 to 1.5 m			Annual Deep Drainage		
	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking
1	Source Depth	100%	High	Source Depth	100%	High	Drainage BC	100%	High
2	CMI	79%	High	Drainage BC	55%	High	CMI	87%	High
3	Drainage BC	47%	High	CMI	33%	High	Vegetation Presence	40%	High
4	Vegetation Presence	47%	High	Upper Lithology	18%	Low to Negligible	Upper Lithology	31%	Moderate
5	Upper Lithology	43%	High	Vegetation Presence	14%	Low to Negligible	Root Depth	8.3%	Low to Negligible
6	Dispersivity	26%	Low to Negligible	Dispersivity	6.7%	Low to Negligible	Interbedded	5.3%	Low to Negligible
7	Root Depth	16%	Low to Negligible	Lower Lithology	3.3%	Low to Negligible	Source Depth	4.3%	Low to Negligible
8	Lower Lithology	6.4%	Low to Negligible	Upper Lithology Thickness	2.5%	Low to Negligible	Lower Lithology	2.8%	Low to Negligible
9	Interbedded	6.2%	Low to Negligible	Slope Runoff	2.5%	Low to Negligible	Slope	2.3%	Low to Negligible
10	Upper Lithology Thickness	5.2%	Low to Negligible	Root Depth	2.0%	Low to Negligible	Dispersivity	1.5%	Low to Negligible
11	Slope Runoff	4.8%	Low to Negligible	Interbedded	1.6%	Low to Negligible	Upper Lithology Thickness	1.1%	Low to Negligible

Notes: Refer to Section 7 for description significance ranking and relative sensitivity.
CMI stands for Climate Moisture Index.

Table 1 Cont'd. Main Effects Sensitivity Rankings for Model Responses

Ranking	Annual Surface Runoff			Minumum Water Table Depth			Maximum Water Table Depth		
	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking
1	CMI	100%	High	Drainage BC	- -	High (estimated)	Drainage BC	- -	High (estimated)
2	Drainage BC	55%	High	CMI	100%	High	CMI	100%	High
3	Upper Lithology	19%	Low to Negligible	Upper Lithology	22%	Low to Negligible	Upper Lithology	40%	High
4	Interbedded	11%	Low to Negligible	Upper Lithology Thickness	8.7%	Low to Negligible	Interbedded	7.9%	Low to Negligible
5	Lower Lithology	6.8%	Low to Negligible	Lower Lithology	8.2%	Low to Negligible	Source Depth	5.9%	Low to Negligible
6	Vegetation Presence	1.2%	Low to Negligible	Source Depth	8.2%	Low to Negligible	Dispersivity	5.9%	Low to Negligible
7	Upper Lithology Thickness	0.7%	Low to Negligible	Vegetation Presence	4.8%	Low to Negligible	Slope Runoff	5.6%	Low to Negligible
8	Slope Runoff	0.3%	Low to Negligible	Dispersivity	4.8%	Low to Negligible	Vegetation Presense	4.5%	Low to Negligible
9	Dispersivity	0.3%	Low to Negligible	Interbedded	2.1%	Low to Negligible	Lower Lithology	4.1%	Low to Negligible
10	Source Depth	0.3%	Low to Negligible	Root Depth	1.3%	Low to Negligible	Upper Lithology Thickness	3.7%	Low to Negligible
11	Root Depth	0.2%	Low to Negligible	Slope Runoff	1.0%	Low to Negligible	Root Depth	0.2%	Low to Negligible

Notes: Refer to Section 7 for description significance ranking and relative sensitivity.
CMI stands for Climate Moisture Index.

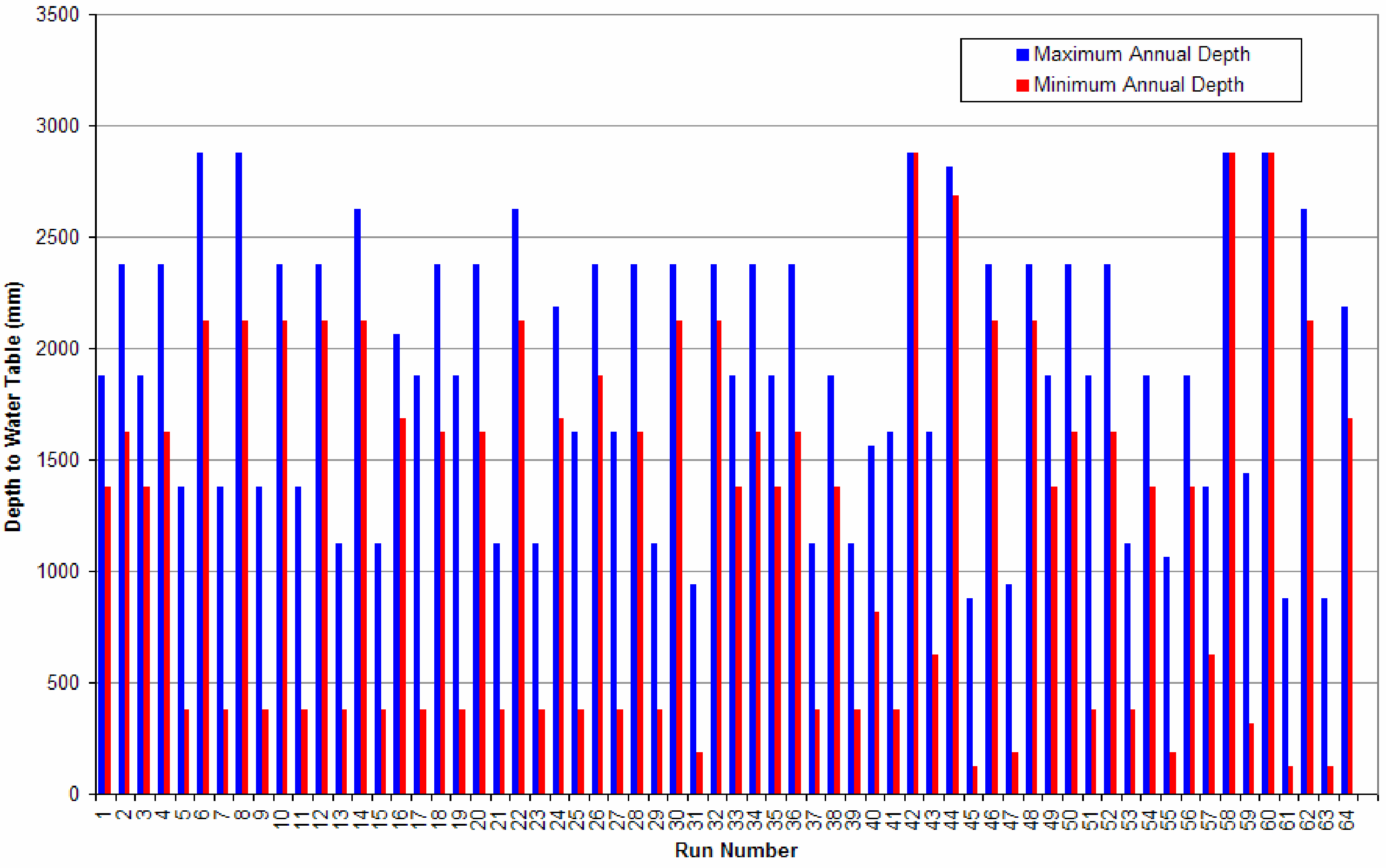
A relatively strong correlation was identified between deep drainage rate and depth to peak chloride concentration and the strength of the correlation is such that other factors, including the CMI, resulted in minimal further variation in the sensitivity analysis results. The majority of the data points are contained within the 95% confidence limits for the regression lines in Figure 8, which implies that the approximate depth of migration of a chloride plume peak can be used to calibrate the annual deep drainage rate. It is important to note that the dataset represents simulated chloride peak migration over a 10-year period and the results should be verified with field results.

The degree of surface runoff was most sensitive to the moisture index and the deep drainage boundary condition. Both factors were found to significantly affect surface runoff at the 5% level. The dry CMI case (Medicine Hat) produced zero runoff, implying a highly sensitive relationship between runoff and moisture availability. For the wet CMI case, the rate of soil drainage at the deep drainage boundary condition had a direct effect on runoff production. A low rate of soil drainage generally produced a shallower water table, which lead to an increased occurrence of surface soil saturation and runoff. Three additional factors that influenced runoff were related to soil lithology (*i.e.*, upper soil lithology texture, presence of a thin interbedded lithology, and lower soil lithology texture). Low conductivity soils produced a higher annual surface runoff.

Of interest is that ground slope (either 0 or 5%) did not produce an appreciable effect on annual surface runoff. The lack of effect of the slope factor was due to the relatively high permeability of the soil surface for both sand and clay loam soils. During the model development process, significant surface runoff effects due to slope were observed for very low permeable soils (*e.g.* hardpan) that are associated with high National Resources Conservation Service (NRCS formerly SCS) runoff curve numbers. The presence of hardpan or relatively low permeability soils at shallow depth intervals due to elevated SAR values may be evaluated during the matrix criteria development process as a special case.

Water table depth was most sensitive to the drainage boundary condition. Minimum and maximum annual water table depths based on a 12 mm/yr deep boundary drainage rate were extracted from the model results and are presented in Figure 9. The range of water table depths extended from 0.4 m to 3 m and the average of the minimum and maximum water table depths were 1.2 and 1.9 m, respectively, for the various texture lithology combinations (*e.g.*, sandy loam over clay loam, uniform sandy loam, interbedded loams). For model runs with the free drainage boundary condition, the water table depth exceeded 10 m in all cases and thus water table depth results are not reported for these drainage scenarios.

Water table depth was also sensitive to upper soil lithology texture in addition to CMI. Thus, secondary to the deep drainage boundary condition the availability of moisture and rate of downward conductance in shallow soils significantly influenced water table depth. A coarse upper soil lithology texture (*i.e.*, sandy loam) was associated with a shallower water table, which may indicate that a more permeable shallow soil layer leads to a more rapid transport of infiltration water to deeper depths that are less influenced by the effects of evapotranspiration. Certain responses (*e.g.* water table depths) that were not anticipated to be sensitive to certain factors demonstrated marginal sensitivity in the analysis. For example, the fifth-ranked factor for the maximum water table depth sensitivity was the chloride source depth. Obviously, these factors should be unrelated. The chloride source depth factor and its apparent relation to maximum water table depth, did not show significant sensitivity at the 10% level. Therefore, the sensitivity of the water table was considered to be not significantly different from zero, which is the expected result.



PTAC	**EQUILIBRIUM ENVIRONMENTAL**	
Figure 9. Minimum and Maximum Modeled Annual Water Table Depths	**09/15/2005**	**Sensitivity Analysis**
	Drawn by: MVC	**Job#: PT-02**

7.2 INTERACTION EFFECTS

Interaction effects measure the combined effect of two or more factors on model response variables. First-order interaction effects (combined effects of two factors) were investigated in this report. The results indicate that few first-order interaction effects produced sensitivities at a 5 or 10% significance level. The interaction effects from two factors that were detected at the 5 or 10% significance level generally had lower net effects in comparison to the most sensitive of the main effects (single factor). Interaction effects higher than first-order were not calculated due to the generally low magnitude of the first-order effects.

Interaction effects on response variables were analyzed graphically using mean interaction effects plots and were examined for statistical significance. Noteworthy interaction effects for peak concentration depth and peak chloride concentration are shown in Figures 10 and 11, respectively. Interaction effects for the remaining model response variables are summarized in Table 2 and are not presented graphically. With regards to the interpretation of the interaction effects plot, each factor is plotted along the diagonal, and the interaction between each factor is plotted at the crossing point of the row and column corresponding to each factor. The steepness of the line joining the two plot points indicates the magnitude of the interaction effect. Lines that plot nearly horizontal show a minimal interaction effect between the two factors. Noticeable interactions (*i.e.*, those with a relatively substantial magnitude of response) are highlighted by a blue box in the figures and the mean effects plots along the diagonal are highlighted in red.

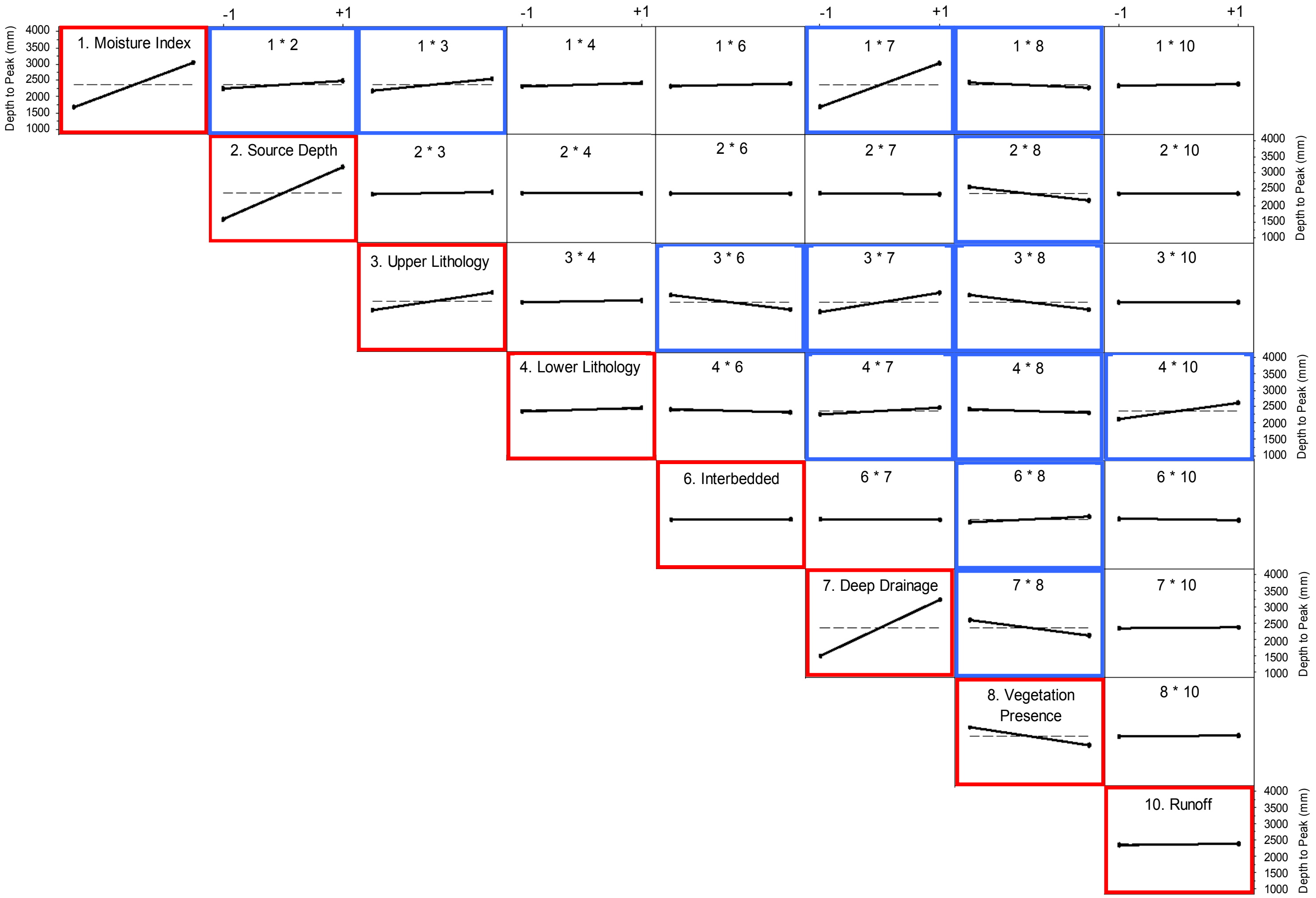
The interaction effects plot for depth to peak concentration (Figure 10) identified eight factors that showed some degree of interaction. One interaction was statistically significant at the 5% level (interaction between CMI and drainage boundary condition). For peak chloride concentration, the interaction effects plot shown in Figure 11 identified nine factors that showed some degree of interaction. Three interactions were significant at the 5% level: 1) moisture index and drainage boundary condition; 2) deep drainage boundary condition and vegetation presence; and, 3) source depth and upper soil lithology texture. The degree of interaction effects is directly comparable to main effects by examining the sensitivity coefficients or the relative sensitivity. Details of the sensitivity coefficients for the top ten ranked interaction effects are contained in Appendix A,Table A-4.

The interaction effects were converted into relative sensitivities by the same method as for the main effects. The magnitudes of the top ten interaction effects (Appendix A, Table A-4) are within a range of 6 to 87 % of the maximum main effect. Although the interaction effects are not larger than the maximum observed main effects, they are nevertheless significant and will require consideration in the development of generic salinity matrix criteria. In general, the majority of the interaction effects were not statistically significant.

7.3 ADDITIONAL FACTORS

7.3.1 Surface Slope and Aspect

An investigation of the effect of slope and aspect on potential evapotranspiration rates was conducted. These factors were not formally evaluated in the sensitivity analysis since their effect was in part accounted for within the boundary values of the CMI factor. In other words, the effect of an increase or decrease of solar radiation input affects the potential evapotranspiration rate and therefore affects the CMI factor. Slope angle is the angle that the ground surface makes with the horizontal and aspect is the cardinal direction that a slope faces.



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EQUILIBRIUM ENVIRONMENTAL

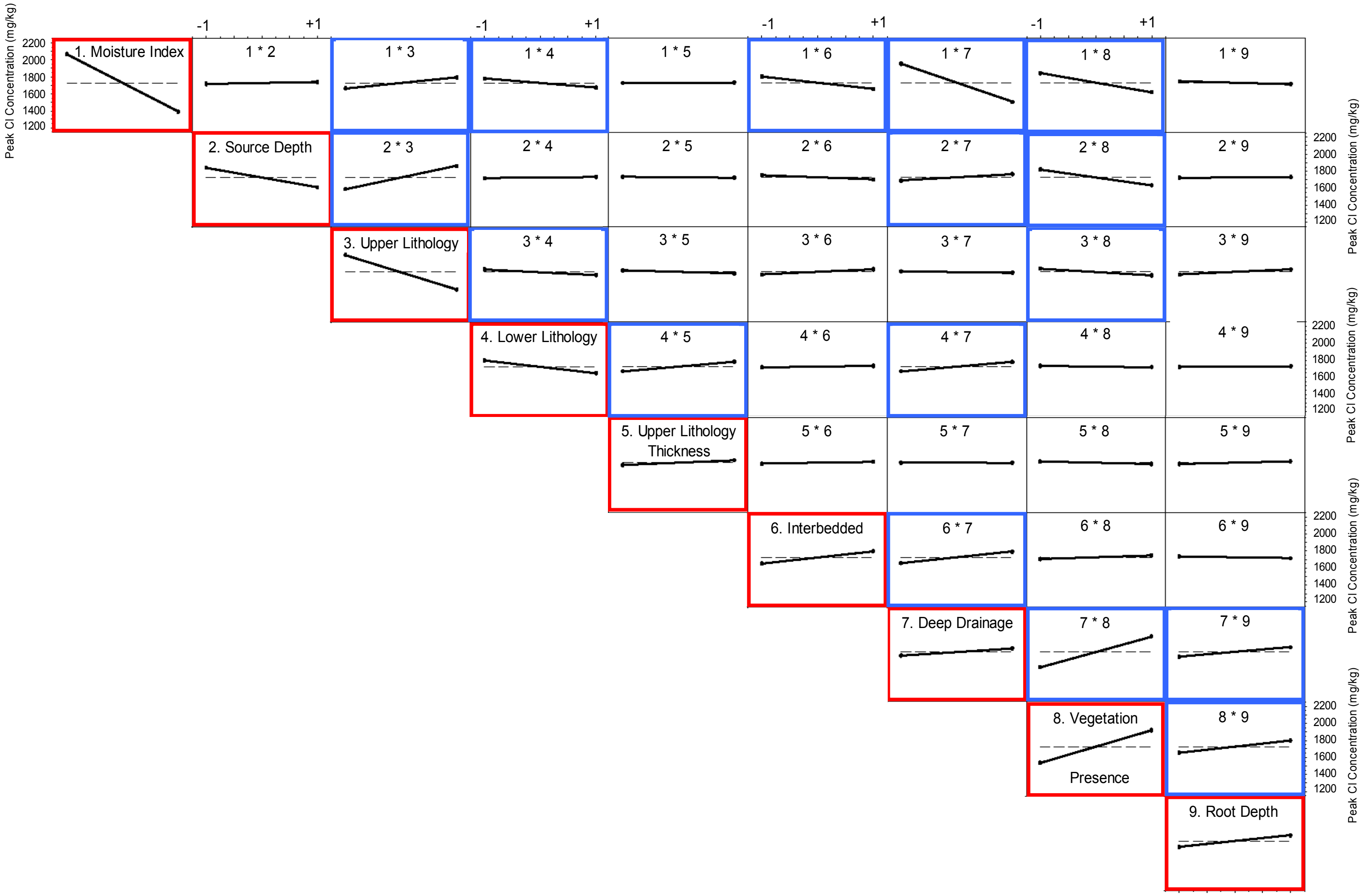
Figure 10. Interaction Effects Plot
Depth to Peak
Soil Chloride Concentration

09/15/2005

Sensitivity Analysis

Drawn by: MVC

Job#: PT-02



PTAC	EQUILIBRIUM ENVIRONMENTAL	
Figure 11. Interaction Effects Plot Peak Soile Chloride Concentration	**09/15/2005**	**Sensitivity Analysis**
	Drawn by: MVC	**Job#: PT-02**

Table 2. Top Ten Interaction Effects Sensitivity Rankings for Model Responses

Ranking	Depth to Peak			Peak Concentration			Breakthrough Depth for 250 mg/L Concentration		
	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking
1	CMI and Drainage BC	78%	High	CMI and Drainage BC	66%	High	CMI and Drainage BC	78%	High
2	Upper Lithology and Drainage	34%	Moderate	Drainage BC and Vegetation Presence	54%	High	Drainage BC and Vegetation Presence	29%	Moderate
3	Lower Lithology and Slope	29%	Low to Negligible	Source Depth and Upper Lithology	40%	High	Upper Lithology and Interbedded	23%	Low to Negligible
4	Drainage and Vegetation Presence	27%	Low to Negligible	CMI and Vegetation Presence	33%	Moderate	Lower Lithology and Slope	20%	Low to Negligible
5	Upper Lithology and Interbedded	26%	Low to Negligible	Source Depth and Vegetation Presence	28%	Low to Negligible	CMI and Interbedded	19%	Low to Negligible
6	Upper Lithology and Vegetation Presence	25.8%	Low to Negligible	CMI and Interbedded	22%	Low to Negligible	CMI and Upper Lithology	17%	Low to Negligible
7	Source Depth and Vegetation Presence	23.8%	Low to Negligible	Vegetation Presence and Root Depth	21%	Low to Negligible	Upper Lithology and Drainage	14%	Low to Negligible
8	CMI and Upper Lithology	21.4%	Low to Negligible	Interbedded and Drainage BC	20%	Low to Negligible	Root Depth and Dispersivity	14%	Low to Negligible
9	CMI and Source Depth	14.0%	Low to Negligible	CMI and Upper Lithology	19%	Low to Negligible	CMI and Dispersivity	13%	Low to Negligible
10	Lower Lithology and Drainage	11.9%	Low to Negligible	Drainage BC and Root Depth	16.8%	Low to Negligible	CMI and Lower Lithology	12.9%	Low to Negligible

Notes: Refer to Section 7 for description significance ranking and relative sensitivity.
CMI stands for Climate Moisture Index.

Table 2 Cont'd. Top Ten Interaction Effects Sensitivity Rankings for Model Responses

Ranking	Maximum Concentration 0 to 1.5 m			Depth of Maximum Concentration 0 to 1.5 m			Annual Deep Drainage		
	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking
1	CMI and Drainage BC	72%	High	Source Depth and Drainage BC	63%	High	CMI and Drainage BC	87%	High
2	Source Depth and Upper Lithology	62%	High	CMI and Source Depth	32%	High	Drainage BC and Vegetation Presence	40%	High
3	Drainage BC and Vegetation Presence	43%	High	Upper Lithology and Root Depth	15%	Low to Negligible	Upper Lithology and Drainage BC	30%	Moderate
4	CMI and Vegetation Presence	37%	High	Source Depth and Vegetation Presence	15%	Low to Negligible	Lower Lithology and Slope	26%	Low to Negligible
5	CMI and Source Depth	33%	Moderate	Interbedded and Vegetation Presence	15%	Low to Negligible	Upper Lithology and Interbedded	23.4%	Low to Negligible
6	Source Depth and Dispersivity	24%	Low to Negligible	CMI and Vegetation Presence	12.9%	Low to Negligible	Upper Lithology and Vegetation Presence	17.0%	Low to Negligible
7	Lower Lithology and Slope	20%	Low to Negligible	Upper Lithology and Slope	12.9%	Low to Negligible	CMI and Source Depth	17.0%	Low to Negligible
8	Upper Lithology and Vegetation Presence	20.0%	Low to Negligible	CMI and Interbedded	12.9%	Low to Negligible	Source Depth and Vegetation Presence	14.9%	Low to Negligible
9	Vegetation Presence and Root Depth	19.1%	Low to Negligible	Source Depth and Upper Lithology	12.5%	Low to Negligible	CMI and Upper Lithology	14.9%	Low to Negligible
10	CMI and Dispersivity	18.3%	Low to Negligible	Vegetation Presence and Root Depth	12.1%	Low to Negligible	CMI and Vegetation Presence	12.8%	Low to Negligible

Notes: Refer to Section 7 for description significance ranking and relative sensitivity.
CMI stands for Climate Moisture Index.

Table 2 Cont'd. Top Ten Interaction Effects Sensitivity Rankings for Model Responses

Ranking	Annual Surface Runoff			Minumum Water Table Depth			Maximum Water Table Depth		
	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking	Factor	Relative Sensitivity	Significance Ranking
1	CMI and Drainage BC	55%	High	CMI and Lower Lithology	33%	High	CMI and Lower Lithology	24%	Low to Negligible
2	Upper Lithology and Interbedded	26%	High	Upper Lithology and Interbedded	20%	Low to Negligible	Upper Lithology and Interbedded	20%	Low to Negligible
3	Lower Lithology and Slope	26%	High	Upper Lithology and Slope	17%	Low to Negligible	CMI and Upper Lithology	20%	Low to Negligible
4	CMI and Upper Lithology	18%	Low to Negligible	Interbedded and Slope	14.6%	Low to Negligible	Source Depth and Vegetation Presence	20%	Low to Negligible
5	CMI and Interbedded	11.6%	Low to Negligible	Lower Lithology and Interbedded	12.4%	Low to Negligible	Upper Lithology and Slope	17%	Low to Negligible
6	Interbedded and Drainage BC	8.3%	Low to Negligible	Lower Lithology and Slope	9.6%	Low to Negligible	Lower Lithology and Interbedded	16%	Low to Negligible
7	Root Depth and Dispersivity	8.3%	Low to Negligible	Upper Lithology Thickness and Slope	9.3%	Low to Negligible	Lower Lithology and Slope	12%	Low to Negligible
8	Lower Lithology and Interbedded	6.6%	Low to Negligible	Source Depth and Dispersivity	9.3%	Low to Negligible	Vegetation Presence and Dispersivity	8%	Low to Negligible
9	Upper Lithology and Slope	6.6%	Low to Negligible	CMI and Upper Lithology	8.5%	Low to Negligible	Interbedded and Slope	6%	Low to Negligible
10	CMI and Lower Lithology	6.6%	Low to Negligible	Source Depth and Vegetation Presence	8.5%	Low to Negligible	Upper Lithology Thickness and Slope	6%	Low to Negligible

Notes: Refer to Section 7 for description significance ranking and relative sensitivity.
CMI stands for Climate Moisture Index.

The effect of increasing slope angle is to increase solar radiation input and therefore increase potential evapotranspiration, depending on the slope aspect. Solar radiation input is a maximum for a south-facing aspect and minimum for a north-facing aspect. Figure 12 shows the relationship between solar radiation intercepting the earth's surface as a function of slope angle and aspect in the northern hemisphere. For a 10 degree slope (18% grade), the maximum increase or decrease in solar radiation input for a north-facing or south-facing slope respectively is approximately +/- 20%. This corresponds to an estimated increase or decrease in potential evapotranspiration of +/- 20%. For an east or west facing 10 degree slope, the difference in solar radiation input is - 2%. A near horizontal slope does not experience significant decreases or increases in solar radiation due to slope aspect. Shevenell (1996) defined a near horizontal slope as a slope with a two degree or less average angle over a one kilometer distance, which is equivalent to a slope of 3.6 %. Therefore, slopes less than 3.6 % can be considered approximately flat and are not likely to experience significant effects in terms of solar radiation input due to slope angle or aspect. The effects of slope and aspect will be evaluated as part of the generic salt transport modeling and remediation criteria matrix development stage of this project study.

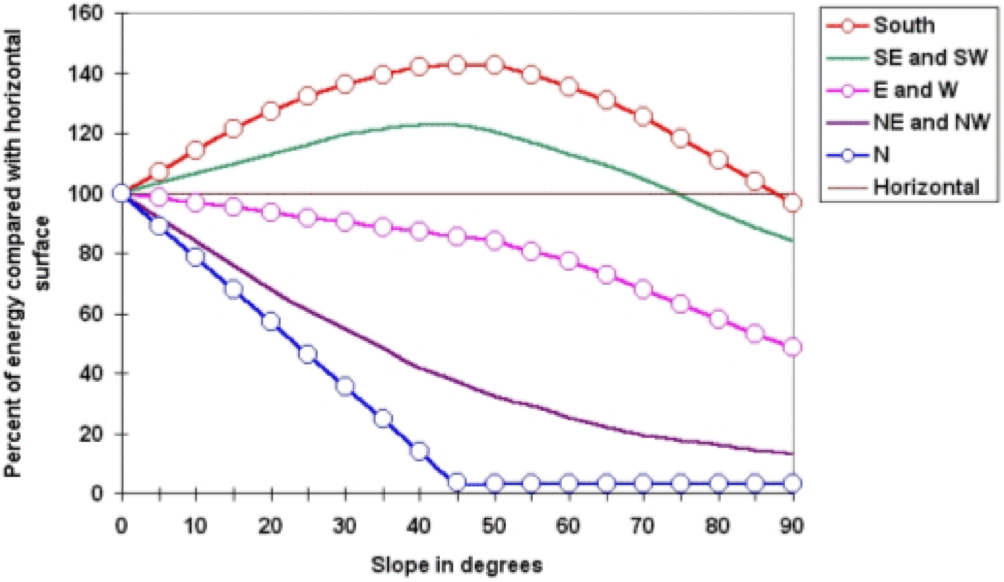


Figure 12. Solar Energy Received on a Slope of Varying Aspect at 45 Degree Northern Latitude (after Guyot, 1999).

For the two boundary values of CMI considered in the sensitivity analysis, the difference in CMI between Whitecourt and Medicine Hat is 709 mm. An increase or decrease in potential evapotranspiration of 20% results in a variation in the CMI range of 13%. Therefore, the effect of a change in potential evapotranspiration on the CMI due to a change in aspect for a slope of 10 degrees is lower in magnitude when compared to the effect on CMI by considering diverse climate regions of Alberta. For a variation of 13% in the CMI range, the net change in each response variable was calculated based on a linear interpolation between responses for the Medicine Hat and Whitecourt CMI boundary values. The results are reported in the table below, and it is important to note that these results are for a simulation duration of 10 years.

Response Variables	Net Response Effect
Depth to Peak Chloride Concentration	+/- 89 mm
Peak Chloride Concentration	+/- 44 mg/kg
Breakthrough Depth for 250 mg/L	+/- 135 mm
Max. Concentration in 0 to 1.5 m depth	+/- 45 mg/kg
Depth of Max. Concentration in 0 to 1.5 m depth	+/- 10 mm
Annual deep drainage	+/- 3 mm
Annual Surface Runoff	+/- 4 mm
Minimum annual water table depth	+/- 92 mm
Maximum annual water table depth	+/- 66 mm

For a duration of 10 years of chloride transport, the effects of a variation of 13% on the CMI range were not great. If a linear extrapolation were used for a 100 year duration of chloride transport, the net response effects in the above table would increase by ten fold. Therefore the duration of chloride transport is a factor in determining the importance of slope and aspect on the net response. Slope and aspect are not the only factors that may contribute to local variations in moisture availability; since, the CMI is composed of a precipitation and potential evapotranspiration component. Factors such as snow sublimation, deep drifting of snow, and concentration of runoff in surface depressions also can affect moisture availability at a site in ways similar to variations in CMI. Adjustments for minor variation in CMI may be required as part of the matrix criteria development process and will be considered in the matrix development phase of the project.

7.3.2 Precipitation Intensity

The effect of precipitation intensity was not formally evaluated as part of the sensitivity analysis, but was nevertheless evaluated informally since literature data suggests it can have a significant effect on net downward moisture (and thus salt) transport (Malone et al., 2004). Three precipitation intensities were examined based on 1-day, 3-day and 7-day moving averages of an identical precipitation time series. The use of averaged precipitation events was carried out as part of the initial modeling process to improve numerical model stability and resulted in a “smoothing” out of intense precipitation events into longer and less intense events that occurred over a greater period of time. This smoothing process would have little effect during winter, when snowfall events are accumulated and melted off in the spring using the HYDRUS-1D snowmelt algorithm. The smoothing effect was most noticeable for rainfall events during the summer season and particularly for sandy soils with a free drainage boundary condition, where a noticeable increase in the net downward transport of a chloride plume was observed. For sandy loam soil with a free drainage rate, a 1-day precipitation time series produced a depth to chloride peak penetration of approximately 9 m after 10 years of simulation. For the same soil profile, a 7-day averaged rainfall rate produced a depth to peak penetration of 6 m. This difference in penetration depths is significant. Although not formally examined, it is probable that the difference in penetration depths for a fine-grained soil would be less. These results indicate that the effect of pulsed infiltration is an important mechanism of downward chloride transport in coarse-grained soil columns. The use of 1-day historically-based precipitation time series is standard practice by Equilibrium, and is a recommended procedure for developing generic subsoil salinity matrix criteria.

8 CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the sensitivity analysis, the following conclusions and recommendations can be made:

1. the three highest factors for determining the depth of transport of the peak chloride concentration were: drainage boundary condition; source depth of the saline water release; and climate moisture index (CMI);
2. the four highest ranked factors for determining the magnitude of the peak chloride concentration were: CMI, longitudinal dispersivity, upper soil lithology texture, and vegetation presence;
3. the five highest ranked factors for breakthrough depth of 250 mg/L chloride concentration were: CMI, drainage boundary condition, source depth of the saline water release, upper soil lithology texture, and longitudinal dispersivity;
4. for model responses related to the water balance: deep drainage; surface runoff; and water table depth, the two highest ranked factors were drainage boundary condition and CMI;
5. significant interaction effects were observed between various factors such as drainage boundary condition, CMI, vegetation presence, and upper soil lithology texture due to combined effects on several response variables for soil water balance (*i.e.*, deep drainage, surface runoff, and water table depth) – certain interaction effects were significant and will require evaluation as part of the matrix criteria development process, however, in general their effect was smaller than the effect of high ranked individual factors;
6. in the free drainage scenario, a significant linear regression was established between the deep drainage rate of the soil column and the depth of transport of the chloride peak – greater drainage rates were associated with greater depths to peak chloride concentration highlighting the importance of this variable in the sensitivity analysis;
7. CMI is an important input factor in the salt transport model and thus generic matrix criteria should be developed separately for various regions of Alberta with different CMI values; and,
8. depth to the water table was identified as an important calibrating factor for the deep drainage rate, which was a high ranked factor in the sensitivity analysis - sites with characterization of seasonal water table depths would be of value in testing generic matrix criteria.

9 CLOSURE

Equilibrium Environmental Inc. has prepared this document for the Petroleum Technology Alliance of Canada solely for the purpose of assisting in the decision making process for the "*Project Study for the Development of Generic Site Assessment Criteria for Salinity below the Root Zone*". Equilibrium does not accept any responsibility for the use of this report for any purpose other than intended or to any third party unless otherwise stated, in whole or in part, and we exercise no duty of care in relation to this report to any third party. Where possible input data was used that was specific to the province of Alberta. In some instances additional data was incorporated from literature sources, which introduced a fraction on non-Alberta specific data into the modeling process. This report and findings herein should be considered in conjunction with subsequent reports produced as part of the PTAC project study. Any questions regarding this document should be directed to Anthony Knafla or Michael Callaghan at (403) 286 7706.

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APPENDIX A

SENSITIVITY ANALYSIS TABLES

Table A-1. Run Matrix for $2^{(11-4)}$ Fractional Factorial Design (after NIST, 2005)

	1	2	3	4	5	6	7	8	9	10	11
Run Number	**Moisture Index**	**Source Depth**	**Upper Lithology**	**Lower Lithology**	**Upper Lithologyg Thickness**	**Interbedded**	**Drainage**	**Vegetation Presence**	**Root Depth**	**Slope**	**Dispersivity**
1	1	-1	-1	-1	-1	-1	-1	1	1	1	-1
2	-1	-1	-1	-1	-1	-1	-1	-1	1	-1	1
3	1	1	-1	-1	-1	-1	-1	-1	-1	1	1
4	-1	1	-1	-1	-1	-1	-1	1	-1	-1	-1
5	1	-1	1	-1	-1	-1	-1	-1	-1	-1	1
6	-1	-1	1	-1	-1	-1	-1	1	-1	1	-1
7	1	1	1	-1	-1	-1	-1	1	1	-1	-1
8	-1	1	1	-1	-1	-1	-1	-1	1	1	1
9	1	-1	-1	1	-1	-1	-1	1	-1	-1	1
10	-1	-1	-1	1	-1	-1	-1	-1	-1	1	-1
11	1	1	-1	1	-1	-1	-1	-1	1	-1	-1
12	-1	1	-1	1	-1	-1	-1	1	1	1	1
13	1	-1	1	1	-1	-1	-1	-1	1	1	-1
14	-1	-1	1	1	-1	-1	-1	1	1	-1	1
15	1	1	1	1	-1	-1	-1	1	-1	1	1
16	-1	1	1	1	-1	-1	-1	-1	-1	-1	-1
17	1	-1	-1	-1	1	-1	-1	1	-1	1	1
18	-1	-1	-1	-1	1	-1	-1	-1	-1	-1	-1
19	1	1	-1	-1	1	-1	-1	-1	1	1	-1
20	-1	1	-1	-1	1	-1	-1	1	1	-1	1
21	1	-1	1	-1	1	-1	-1	-1	1	-1	-1
22	-1	-1	1	-1	1	-1	-1	1	1	1	1
23	1	1	1	-1	1	-1	-1	1	-1	-1	1
24	-1	1	1	-1	1	-1	-1	-1	-1	1	-1
25	1	-1	-1	1	1	-1	-1	1	1	-1	-1
26	-1	-1	-1	1	1	-1	-1	-1	1	1	1
27	1	1	-1	1	1	-1	-1	-1	-1	-1	1
28	-1	1	-1	1	1	-1	-1	1	-1	1	-1
29	1	-1	1	1	1	-1	-1	-1	-1	1	1
30	-1	-1	1	1	1	-1	-1	1	-1	-1	-1
31	1	1	1	1	1	-1	-1	1	1	1	-1
32	-1	1	1	1	1	-1	-1	-1	1	-1	1
33	1	-1	-1	-1	-1	1	-1	1	1	-1	1
34	-1	-1	-1	-1	-1	1	-1	-1	1	1	-1
35	1	1	-1	-1	-1	1	-1	-1	-1	-1	-1
36	-1	1	-1	-1	-1	1	-1	1	-1	1	1
37	1	-1	1	-1	-1	1	-1	-1	-1	1	-1
38	-1	-1	1	-1	-1	1	-1	1	-1	-1	1
39	1	1	1	-1	-1	1	-1	1	1	1	1
40	-1	1	1	-1	-1	1	-1	-1	1	-1	-1
41	1	-1	-1	1	-1	1	-1	1	-1	1	-1
42	-1	-1	-1	1	-1	1	-1	-1	-1	-1	1
43	1	1	-1	1	-1	1	-1	-1	1	1	1
44	-1	1	-1	1	-1	1	-1	1	1	-1	-1
45	1	-1	1	1	-1	1	-1	-1	1	-1	1
46	-1	-1	1	1	-1	1	-1	1	1	1	-1
47	1	1	1	1	-1	1	-1	1	-1	-1	-1
48	-1	1	1	1	-1	1	-1	-1	-1	1	1
49	1	-1	-1	-1	1	1	-1	1	-1	-1	-1
50	-1	-1	-1	-1	1	1	-1	-1	-1	1	1
51	1	1	-1	-1	1	1	-1	-1	1	-1	1
52	-1	1	-1	-1	1	1	-1	1	1	1	-1
53	1	-1	1	-1	1	1	-1	-1	1	1	1
54	-1	-1	1	-1	1	1	-1	1	1	-1	-1
55	1	1	1	-1	1	1	-1	1	-1	1	-1
56	-1	1	1	-1	1	1	-1	-1	-1	-1	1
57	1	-1	-1	1	1	1	-1	1	1	1	1
58	-1	-1	-1	1	1	1	-1	-1	1	-1	-1
59	1	1	-1	1	1	1	-1	-1	-1	1	-1
60	-1	1	-1	1	1	1	-1	1	-1	-1	1
61	1	-1	1	1	1	1	-1	-1	-1	-1	-1
62	-1	-1	1	1	1	1	-1	1	-1	1	1
63	1	1	1	1	1	1	-1	1	1	-1	1
64	-1	1	1	1	1	1	-1	-1	1	1	-1

Table A-1 Cont'd. Run Matrix for $2^{(11-4)}$ Fractional Factorial Design (after NIST, 2005)

	1	2	3	4	5	6	7	8	9	10	11
Run Number	Moisture Index	Source Depth	Upper Lithology	Lower Lithology	Upper Litholoyg Thickness	Interbedded	Drainage	Vegetation Presence	Root Depth	Slope	Dispersivity
65	1	-1	-1	-1	-1	-1	1	-1	1	1	1
66	-1	-1	-1	-1	-1	-1	1	1	1	-1	-1
67	1	1	-1	-1	-1	-1	1	1	-1	1	-1
68	-1	1	-1	-1	-1	-1	1	-1	-1	-1	1
69	1	-1	1	-1	-1	-1	1	1	-1	-1	-1
70	-1	-1	1	-1	-1	-1	1	-1	-1	1	1
71	1	1	1	-1	-1	-1	1	-1	1	-1	1
72	-1	1	1	-1	-1	-1	1	1	1	1	-1
73	1	-1	-1	1	-1	-1	1	-1	-1	-1	-1
74	-1	-1	-1	1	-1	-1	1	1	-1	1	1
75	1	1	-1	1	-1	-1	1	1	1	-1	1
76	-1	1	-1	1	-1	-1	1	-1	1	1	-1
77	1	-1	1	1	-1	-1	1	1	1	1	1
78	-1	-1	1	1	-1	-1	1	-1	1	-1	-1
79	1	1	1	1	-1	-1	1	-1	-1	1	-1
80	-1	1	1	1	-1	-1	1	1	-1	-1	1
81	1	-1	-1	-1	1	-1	1	-1	-1	1	-1
82	-1	-1	-1	-1	1	-1	1	1	-1	-1	1
83	1	1	-1	-1	1	-1	1	1	1	1	1
84	-1	1	-1	-1	1	-1	1	-1	1	-1	-1
85	1	-1	1	-1	1	-1	1	1	1	-1	1
86	-1	-1	1	-1	1	-1	1	-1	1	1	-1
87	1	1	1	-1	1	-1	1	-1	-1	-1	-1
88	-1	1	1	-1	1	-1	1	1	-1	1	1
89	1	-1	-1	1	1	-1	1	-1	1	-1	1
90	-1	-1	-1	1	1	-1	1	1	1	1	-1
91	1	1	-1	1	1	-1	1	1	-1	-1	-1
92	-1	1	-1	1	1	-1	1	-1	-1	1	1
93	1	-1	1	1	1	-1	1	1	-1	1	-1
94	-1	-1	1	1	1	-1	1	-1	-1	-1	1
95	1	1	1	1	1	-1	1	-1	1	1	1
96	-1	1	1	1	1	-1	1	1	1	-1	-1
97	1	-1	-1	-1	-1	1	1	-1	1	-1	-1
98	-1	-1	-1	-1	-1	1	1	1	1	1	1
99	1	1	-1	-1	-1	1	1	1	-1	-1	1
100	-1	1	-1	-1	-1	1	1	-1	-1	1	-1
101	1	-1	1	-1	-1	1	1	1	-1	1	1
102	-1	-1	1	-1	-1	1	1	-1	-1	-1	-1
103	1	1	1	-1	-1	1	1	-1	1	1	-1
104	-1	1	1	-1	-1	1	1	1	1	-1	1
105	1	-1	-1	1	-1	1	1	-1	-1	1	1
106	-1	-1	-1	1	-1	1	1	1	-1	-1	-1
107	1	1	-1	1	-1	1	1	1	1	1	-1
108	-1	1	-1	1	-1	1	1	-1	1	-1	1
109	1	-1	1	1	-1	1	1	1	1	-1	-1
110	-1	-1	1	1	-1	1	1	-1	1	1	1
111	1	1	1	1	-1	1	1	-1	-1	-1	1
112	-1	1	1	1	-1	1	1	1	-1	1	-1
113	1	-1	-1	-1	1	1	1	-1	-1	-1	1
114	-1	-1	-1	-1	1	1	1	1	-1	1	-1
115	1	1	-1	-1	1	1	1	1	1	-1	-1
116	-1	1	-1	-1	1	1	1	-1	1	1	1
117	1	-1	1	-1	1	1	1	1	1	1	-1
118	-1	-1	1	-1	1	1	1	-1	1	-1	1
119	1	1	1	-1	1	1	1	-1	-1	1	1
120	-1	1	1	-1	1	1	1	1	-1	-1	-1
121	1	-1	-1	1	1	1	1	-1	1	1	-1
122	-1	-1	-1	1	1	1	1	1	1	-1	1
123	1	1	-1	1	1	1	1	1	-1	1	1
124	-1	1	-1	1	1	1	1	-1	-1	-1	-1
125	1	-1	1	1	1	1	1	1	-1	-1	1
126	-1	-1	1	1	1	1	1	-1	-1	1	-1
127	1	1	1	1	1	1	1	-1	1	-1	-1
128	-1	1	1	1	1	1	1	1	1	1	1

Table A-2. Run Results for Measured Response Variables

Run Number	Depth to Peak (mm)	Peak Conc. (mg/kg)	Depth of >250 mg/L (mm)	Depth of Max. Conc. 0 to 1.5 m (mm)	Max. Conc. 0 to 1.5 m (mg/kg)	Annual Deep Drainage (mm)	Annual Surface Runoff (mm)	Water Table Depth - Max (mm)	Water Table Depth - Min (mm)
1	625	2390	2625	625	2390	11.9	114.1	1875	1375
2	625	1905	3375	625	1905	11.9	0	2375	1625
3	2375	1612	4625	1375	848	11.9	114	1875	1375
4	2375	2063	4125	1375	812	11.9	0	2375	1625
5	1125	1657	3375	1125	1657	11.9	79.1	1375	375
6	625	1922	2875	625	1922	11.9	0	2875	2125
7	2375	2038	4125	1375	766	11.9	79.1	1375	375
8	2375	1396	4625	1375	840	11.9	0	2875	2125
9	625	1579	4125	625	1579	11.9	112.1	1375	375
10	625	2280	2875	625	2280	11.9	0	2375	2125
11	2375	1556	4625	1375	967	11.9	111.9	1375	375
12	2625	1392	4875	1375	797	11.9	0	2375	2125
13	875	1633	3875	875	1633	11.9	75.5	1125	375
14	625	1207	4375	625	1207	11.9	0	2625	2125
15	875	780	6875	875	780	11.9	75.5	1125	375
16	2313	1691	4438	1563	949	11.9	0	2063	1688
17	625	1922	3125	625	1922	11.9	114.1	1875	375
18	625	2450	2625	625	2450	11.9	0	2375	1625
19	2375	2023	4125	1375	857	11.9	114	1875	375
20	2375	1614	4625	1375	808	11.9	0	2375	1625
21	875	1899	3125	875	1899	11.9	79.6	1125	375
22	625	1273	3875	625	1273	11.9	0	2625	2125
23	2375	981	4875	1375	915	11.9	79.6	1125	375
24	2313	1869	4313	1438	836	11.9	0	2188	1688
25	625	2355	2625	625	2355	11.9	115.7	1625	375
26	625	1785	3375	625	1785	11.9	0	2375	1875
27	2375	1302	5125	1375	893	11.9	115.4	1625	375
28	2375	2076	4375	1375	665	11.9	0	2375	1625
29	875	985	6125	875	985	11.9	75.5	1125	375
30	375	1916	3125	375	1916	11.9	0	2375	2125
31	2313	1095	5313	1438	899	11.9	77.2	938	188
32	2375	1099	5125	1375	803	11.9	0	2375	2125
33	625	1922	3125	625	1922	11.9	114	1875	1375
34	625	1905	3375	625	1905	11.9	0	2375	1625
35	2375	1612	4625	1375	848	11.9	114	1875	1375
36	2375	1614	4625	1375	808	11.9	0	2375	1625
37	625	1667	4125	625	1667	11.9	94.6	1125	375
38	625	1948	3625	625	1948	11.9	0	1875	1375
39	2625	1112	5375	1375	848	11.9	95.2	1125	375
40	2563	1909	4313	1438	887	11.9	0	1563	813
41	1125	2011	3125	1125	2011	11.9	78.4	1625	375
42	375	1839	3625	375	1839	11.9	0	2875	2875
43	2375	1082	5375	1375	922	11.9	77.8	1625	625
44	2438	2282	4313	1438	853	11.9	0	2813	2688
45	875	895	6375	875	895	11.9	79.9	875	125
46	375	1916	3125	375	1916	11.9	0	2375	2125
47	2313	1062	5313	1438	1062	11.9	80.2	938	188
48	2375	1099	5125	1375	803	11.9	0	2375	2125
49	625	2390	2625	625	2390	11.9	114	1875	1375
50	625	1905	3375	625	1905	11.9	0	2375	1625
51	2375	1612	4625	1375	849	11.9	114.2	1875	375
52	2375	2064	4125	1375	811	11.9	0	2375	1625
53	625	1667	4125	625	1667	11.9	94.6	1125	375
54	625	2575	2875	625	2575	11.9	0	1875	1375
55	2563	1752	4438	1438	950	11.9	102.4	1063	188
56	2625	1441	4625	1375	683	11.9	0	1875	1375
57	1125	1506	4125	1125	1506	11.9	77.8	1375	625
58	375	2769	3375	375	2769	11.9	0	2875	2875
59	2313	1804	4438	1438	972	11.9	78.5	1438	313
60	2375	1503	4625	1375	971	11.9	0	2875	2875
61	875	1553	4125	875	1553	11.9	79.9	875	125
62	625	1207	4375	625	1207	11.9	0	2625	2125
63	1375	743	7125	1375	743	11.9	79.9	875	125
64	2313	1691	4438	1438	837	11.9	0	2188	1688

Table A-2 Cont'd. Run Results for Measured Response Variables

Run Number	Depth to Peak (mm)	Peak Conc. (mg/kg)	Depth of >250 mg/L (mm)	Depth of Max. Conc. 0 to 1.5 m (mm)	Max. Conc. 0 to 1.5 m (mg/kg)	Annual Deep Drainage (mm)	Annual Surface Runoff (mm)	Water Table Depth - Max (mm)	Water Table Depth - Min
65	2125	1062	5625	1375	914	61.7	79.7	na	na
66	1125	4002	2625	1125	3637	2	0	na	na
67	3375	1731	5625	1375	65	51.7	69.6	na	na
68	2625	1487	5125	1375	659	18.4	0	na	na
69	3813	1523	6313	1438	47	97	0	na	na
70	1875	958	5125	1375	878	36.3	0	na	na
71	6875	653	9875	1375	19	173.9	0	na	na
72	1375	2796	3375	1375	2796	1.9	0	na	na
73	2375	1125	5125	1375	1211	63.1	78.5	na	na
74	625	2185	3125	625	2185	11.7	0	na	na
75	3125	1067	6125	1375	700	22.4	68.1	na	na
76	2875	1948	4875	1375	390	20.2	0	na	na
77	4375	716	9375	1375	254	82.2	6.8	na	na
78	2375	1576	4875	1375	867	49	0	na	na
79	9125	1071	9875	1375	0	181.8	9	na	na
80	2625	1403	4875	1375	703	9.9	0	na	na
81	1875	1585	4375	1375	1269	61.7	79.7	na	na
82	625	2219	3125	625	2219	10.2	0	na	na
83	2625	1358	5125	1375	929	18.8	71.4	na	na
84	2625	2062	4375	1375	511	18.4	0	na	na
85	4125	969	8375	1375	240	89	0	na	na
86	2125	1581	4625	1375	934	47.9	0	na	na
87	7875	1269	9875	1375	0	189.9	0	na	na
88	2375	1362	4625	1375	847	7.3	0	na	na
89	2125	1061	6375	1375	912	61.7	79.4	na	na
90	1125	4009	2125	1125	4009	2.3	0	na	na
91	3375	1730	6125	1375	64	51.9	69.4	na	na
92	2625	1493	5125	1375	659	18.6	0	na	na
93	5188	1222	8188	1438	7	111.9	4.4	na	na
94	2625	923	6625	1375	685	49	0	na	na
95	9875	528	9875	1375	8	181.8	9	na	na
96	1375	3494	3375	1375	3494	1.5	0	na	na
97	4125	1438	7125	1375	82	123.3	2.3	na	na
98	1375	3412	2375	1125	3423	2	0	na	na
99	5125	865	9875	1375	127	95.9	1	na	na
100	2375	2647	4375	1375	343	15.5	0	na	na
101	3625	957	7875	1375	340	89	30.7	na	na
102	1625	2048	4125	1375	1342	41.8	0	na	na
103	5875	1479	8875	1375	0	124.6	38.2	na	na
104	1875	2871	3625	1375	1323	1.8	0	na	na
105	4125	808	9375	1375	257	122.7	3.1	na	na
106	375	4157	2375	375	4157	5.2	0	na	na
107	5125	1613	7625	1375	2	85.7	3.2	na	na
108	2375	1661	5125	1375	692	15.5	0	na	na
109	2875	1943	5625	1375	150	69.7	19.8	na	na
110	1875	1337	5375	875	995	41.8	0	na	na
111	6625	766	9875	1375	35	139.2	19.9	na	na
112	2625	2425	4375	1375	494	13.1	0	na	na
113	4125	805	9625	1375	253	123.3	2.3	na	na
114	375	4157	2375	375	4157	5.2	0	na	na
115	5125	1620	7625	1375	2	86.4	2.4	na	na
116	2375	1661	5125	1375	692	15.5	0	na	na
117	2625	2200	4875	1375	424	53.3	36.1	na	na
118	1875	1337	5375	875	994	41.8	0	na	na
119	5625	779	9875	1375	47	124.6	38.2	na	na
120	2625	2425	4375	1375	494	13.1	0	na	na
121	4125	1442	7125	1375	84	122.7	3.1	na	na
122	1125	3423	2375	1125	3423	2	0	na	na
123	5125	871	9875	1375	130	94.7	2.4	na	na
124	2375	2647	4375	1375	343	15.5	0	na	na
125	3625	914	8375	1375	281	98.5	19.6	na	na
126	1625	2049	4125	1375	1343	41.8	0	na	na
127	6625	1483	9625	1375	0	139.2	19.9	na	na
128	1875	2871	3625	1375	1323	1.8	0	na	na

Table A-3. Detailed Main Effects Sensitivity Rankings

	Depth to Peak					Peak Concentration					Breakthrough Depth to 250 mg/L				
Ranking	**Factor**	**Sensitivity (mm)**	**Relative Sensitivity**	**Significant at 5% Level**	**Significant at 10% Level**	**Factor**	**Sensitivity (mg/kg)**	**Relative Sensitivity**	**Significant at 5% Level**	**Significant at 10% Level**	**Factor**	**Sensitivity (mm)**	**Relative Sensitivity**	**Significant at 5% Level**	**Significant at 10% Level**
1	Drainage BC	1726	100%	Yes	Yes	Moisture Index	672	100%	Yes	Yes	Moisture Index	2075	100%	Yes	Yes
2	Source Depth	1610	93%	Yes	Yes	Dispersivity	636	95%	Yes	Yes	Drainage BC	1755	85%	Yes	Yes
3	Moisture Index	1374	80%	Yes	Yes	Upper Lithology	399	59%	Yes	Yes	Source Depth	1105	53%	Yes	Yes
4	Vegetation Presence	560	32%	No	Yes	Vegetation Presence	386	57%	Yes	Yes	Upper Lithology	886	43%	Yes	Yes
5	Upper Lithology	548	32%	No	Yes	Source Depth	238	35%	No	Yes	Dispersivity	880	42%	Yes	Yes
6	Lower Lithology	110	6.4%	No	No	Lower Lithology	155	23%	No	No	Vegetation Presence	694	33%	No	Yes
7	Root Depth	44	2.5%	No	No	Interbedded	139	21%	No	No	Lower Lithology	460	22%	No	No
8	Slope Runoff	38	2.2%	No	No	Root Depth	133	20%	No	No	Interbedded	278	13%	No	No
9	Upper Lithology Thickness	15	0.9%	No	No	Drainage BC	91	14%	No	No	Root Depth	233	11%	No	No
10	Interbedded	15	0.9%	No	No	Upper Lithology Thickness	58	8.6%	No	No	Slope Runoff	30	1.4%	No	No
11	Dispersivity	7	0.4%	No	No	Slope Runoff	55	8.2%	No	No	Upper Lithology Thickness	15	0.7%	No	No

Note: All model responses calculated for a 10 year simulation duration.

Table A-3 Cont'd. Detailed Main Effects Sensitivity Rankings

	Max. Conc. 0 to 1.5 m					Depth of Max. Conc. 0 to 1.5 m Depth					Deep Drainage				
Ranking	**Factor**	**Sensitivity (mg/kg)**	**Relative Sensitivity**	**Significant at 5% Level**	**Significant at 10% Level**	**Factor**	**Sensitivity (mm)**	**Relative Sensitivity**	**Significant at 5% Level**	**Significant at 10% Level**	**Factor**	**Sensitivity (mm)**	**Relative Sensitivity**	**Significant at 5% Level**	**Significant at 10% Level**
1	Source Depth	869	100%	Yes	Yes	Source Depth	448	100%	Yes	Yes	Drainage BC	47.0	100%	Yes	Yes
2	Moisture Index	687	79%	Yes	Yes	Drainage BC	247	55%	Yes	Yes	Moisture Index	40.9	87%	Yes	Yes
3	Drainage BC	410	47%	Yes	Yes	Moisture Index	149	33%	Yes	Yes	Vegetation Presence	18.6	40%	Yes	Yes
4	Vegetation Presence	406	47%	Yes	Yes	Upper Lithology	81	18%	No	No	Upper Lithology	14.4	31%	No	Yes
5	Upper Lithology	378	43%	Yes	Yes	Vegetation Presence	62	14%	No	No	Root Depth	3.9	8.3%	No	No
6	Dispersivity	229	26%	No	No	Dispersivity	30	6.7%	No	No	Interbedded	2.5	5.3%	No	No
7	Root Depth	135	16%	No	No	Lower Lithology	15	3.3%	No	No	Source Depth	2.0	4.3%	No	No
8	Lower Lithology	56	6.4%	No	No	Upper Lithology Thickness	11	2.5%	No	No	Lower Lithology	1.3	2.8%	No	No
9	Interbedded	54	6.2%	No	No	Slope Runoff	11	2.5%	No	No	Slope	1.1	2.3%	No	No
10	Upper Lithology Thickness	45	5.2%	No	No	Root Depth	9	2.0%	No	No	Dispersivity	0.7	1.5%	No	No
11	Slope Runoff	42	4.8%	No	No	Interbedded	7	1.6%	No	No	Upper Lithology Thickness	0.5	1.1%	No	No

Note: All model responses calculated for a 10 year simulation duration.

Table A-3 Cont'd. Detailed Main Effects Sensitivity Rankings

	Surface Runoff					Minimum Water Table Depth					Maximum Water Table Depth				
Ranking	**Factor**	**Sensitivity (mm)**	**Relative Sensitivity**	**Significant at 5% Level**	**Significant at 10% Level**	**Factor**	**Sensitivity (mm)**	**Relative Sensitivity**	**Significant at 5% Level**	**Significant at 10% Level**	**Factor**	**Sensitivity (mm)**	**Relative Sensitivity**	**Significant at 5% Level**	**Significant at 10% Level**
1	Moisture Index	60.5	100%	Yes	Yes	Drainage BC	>8792	- -	- -	- -	Drainage BC	>8108	- -	- -	- -
2	Drainage BC	33.4	55%	Yes	Yes	Moisture Index	1408	100%	Yes	Yes	Moisture Index	1010	100%	Yes	Yes
3	Upper Lithology	11.2	19%	No	No	Upper Lithology	303	22%	No	No	Upper Lithology	404	40%	Yes	Yes
4	Interbedded	6.9	11%	No	No	Upper Lithology Thickness	123	8.7%	No	No	Interbedded	80	7.9%	No	No
5	Lower Lithology	4.1	6.8%	No	No	Lower Lithology	115	8.2%	No	No	Source Depth	60	5.9%	No	No
6	Vegetation Presence	0.7	1.2%	No	No	Source Depth	115	8.2%	No	No	Dispersivity	60	5.9%	No	No
7	Upper Lithology Thickness	0.4	0.7%	No	No	Vegetation Presence	68	4.8%	No	No	Slope Runoff	57	5.6%	No	No
8	Slope Runoff	0.2	0.3%	No	No	Dispersivity	68	4.8%	No	No	Vegetation Presense	45	4.5%	No	No
9	Dispersivity	0.2	0.3%	No	No	Interbedded	29	2.1%	No	No	Lower Lithology	41	4.1%	No	No
10	Source Depth	0.2	0.3%	No	No	Root Depth	18	1.3%	No	No	Upper Lithology Thickness	37	3.7%	No	No
11	Root Depth	0.1	0.2%	No	No	Slope Runoff	14	1.0%	No	No	Root Depth	2	0.2%	No	No

Note: All model responses calculated for a 10 year simulation duration.

Table A-4. Detailed Sensitivity Ranking for Top Ten Interaction Effects

	Depth to Peak					Peak Concentration					Depth to 250 mg/L				
Ranking	Factor	Sensitivity Coefficient (mm)	Relative Response	Significant at 5% Level	Significant at 10% Level	Factor	Sensitivity Coefficient (mg/kg)	Relative Response	Significant at 5% Level	Significant at 10% Level	Factor	Sensitivity Coefficient (mm)	Relative Response	Significant at 5% Level	Significant at 10% Level
1	CMI and Drainage BC	1345	78%	Yes	Yes	CMI and Drainage BC	446	66%	Yes	Yes	CMI and Drainage BC	1612	78%	Yes	Yes
2	Upper Lithology and Drainage	593	34%	No	Yes	Drainage BC and Vegetation Presence	361	54%	Yes	Yes	Drainage BC and Vegetation Presence	603	29%	No	Yes
3	Lower Lithology and Slope	507	29%	No	No	Source Depth and Upper Lithology	272	40%	Yes	Yes	Upper Lithology and Interbedded	472	23%	No	No
4	Drainage and Vegetation Presence	472	27%	No	No	CMI and Vegetation Presence	224	33%	No	Yes	Lower Lithology and Slope	411	20%	No	No
5	Upper Lithology and Interbedded	446	26%	No	No	Source Depth and Vegetation Presence	186	28%	No	No	CMI and Interbedded	390	19%	No	No
6	Upper Lithology and Vegetation Presence	446	26%	No	No	CMI and Interbedded	148	22%	No	No	CMI and Upper Lithology	353	17%	No	No
7	Source Depth and Vegetation Presence	411	24%	No	No	Vegetation Presence and Root Depth	142	21%	No	No	Upper Lithology and Drainage	286	14%	No	No
8	CMI and Upper Lithology	370	21%	No	No	Interbedded and Drainage BC	135	20%	No	No	Root Depth and Dispersivity	282	14%	No	No
9	CMI and Source Depth	241	14%	No	No	CMI and Upper Lithology	127	19%	No	No	CMI and Dispersivity	269	13%	No	No
10	Lower Lithology and Drainage	206	12%	No	No	Drainage BC and Root Depth	113	17%	No	No	CMI and Lower Lithology	267	13%	No	No

Note: All model responses calculated for a 10 year simulation duration.

Table A-4 Cont'd. Detailed Sensitivity Ranking for Top Ten Interaction Effects

	Maximum Concentration in 0 to 1.5 m Interval					**Depth of Maximum Concentration in 0 to 1.5 m Interval**					**Annual Deep Drainage**				
Ranking	**Factor**	**Sensitivity Coefficient (mg/kg)**	**Relative Response**	**Significant at 5% Level**	**Significant at 10% Level**	**Factor**	**Sensitivity Coefficient (mm)**	**Relative Response**	**Significant at 5% Level**	**Significant at 10% Level**	**Factor**	**Sensitivity Coefficient (mm)**	**Relative Response**	**Significant at 5% Level**	**Significant at 10% Level**
1	CMI and Drainage BC	630	72%	Yes	Yes	Source Depth and Drainage BC	280	63%	Yes	Yes	CMI and Drainage BC	41	87%	Yes	Yes
2	Source Depth and Upper Lithology	541	62%	Yes	Yes	CMI and Source Depth	144	32%	Yes	Yes	Drainage BC and Vegetation Presence	19	40%	Yes	Yes
3	Drainage BC and Vegetation Presence	376	43%	Yes	Yes	Upper Lithology and Root Depth	69	15%	No	No	Upper Lithology and Drainage BC	14	30%	No	Yes
4	CMI and Vegetation Presence	325	37%	Yes	Yes	Source Depth and Vegetation Presence	67	15%	No	No	Lower Lithology and Slope	12	26%	No	No
5	CMI and Source Depth	291	33%	No	Yes	Interbedded and Vegetation Presence	65	15%	No	No	Upper Lithology and Interbedded	11	23%	No	No
6	Source Depth and Dispersivity	205	24%	No	No	CMI and Vegetation Presence	58	13%	No	No	Upper Lithology and Vegetation Presence	8	17%	No	No
7	Lower Lithology and Slope	175	20%	No	No	Upper Lithology and Slope	58	13%	No	No	CMI and Source Depth	8	17%	No	No
8	Upper Lithology and Vegetation Presence	174	20%	No	No	CMI and Interbedded	58	13%	No	No	Source Depth and Vegetation Presence	7	15%	No	No
9	Vegetation Presence and Root Depth	166	19%	No	No	Source Depth and Upper Lithology	56	13%	No	No	CMI and Upper Lithology	7	15%	No	No
10	CMI and Dispersivity	159	18%	No	No	Vegetation Presence and Root Depth	54	12%	No	No	CMI and Vegetation Presence	6	13%	No	No

Note: All model responses calculated for a 10 year simulation duration.

Table A-4 Cont'd. Detailed Sensitivity Ranking for Top Ten Interaction Effects

	Annual Surface Runoff					Minimum Water Table Depth					Maximum Water Table Depth				
Ranking	Factor	Sensitivity Coefficient (mm)	Relative Response	Significant at 5% Level	Significant at 10% Level	Factor	Sensitivity Coefficient (mm)	Relative Response	Significant at 5% Level	Significant at 10% Level	Factor	Sensitivity Coefficient (mm)	Relative Response	Significant at 5% Level	Significant at 10% Level
1	CMI and Drainage BC	33	55%	Yes	Yes	CMI and Lower Lithology	459	33%	Yes	Yes	CMI and Lower Lithology	240	24%	No	No
2	Upper Lithology and Interbedded	16	26%	Yes	Yes	Upper Lithology and Interbedded	283	20%	No	No	Upper Lithology and Interbedded	205	20%	No	No
3	Lower Lithology and Slope	16	26%	Yes	Yes	Upper Lithology and Slope	244	17%	No	No	CMI and Upper Lithology	205	20%	No	No
4	CMI and Upper Lithology	11	18%	No	No	Interbedded and Slope	205	15%	No	No	Source Depth and Vegetation Presence	205	20%	No	No
5	CMI and Interbedded	7	12%	No	No	Lower Lithology and Interbedded	174	12%	No	No	Upper Lithology and Slope	174	17%	No	No
6	Interbedded and Drainage BC	5	8%	No	No	Lower Lithology and Slope	135	10%	No	No	Lower Lithology and Interbedded	166	16%	No	No
7	Root Depth and Dispersivity	5	8%	No	No	Upper Lithology Thickness and Slope	131	9%	No	No	Lower Lithology and Slope	119	12%	No	No
8	Lower Lithology and Interbedded	4	7%	No	No	Source Depth and Dispersivity	131	9%	No	No	Vegetation Presence and Dispersivity	76	8%	No	No
9	Upper Lithology and Slope	4	7%	No	No	CMI and Upper Lithology	119	8%	No	No	Interbedded and Slope	64	6%	No	No
10	CMI and Lower Lithology	4	7%	No	No	Source Depth and Vegetation Presence	119	8%	No	No	Upper Lithology Thickness and Slope	60	6%	No	No

Note: All model responses calculated for a 10 year simulation duration.