APPENDIX H

Mathematical Modelling of Solute Transport in Rock Fractures

Mathematical Modelling of Solute Transport in Rock Fractures

In order to evaluate the potential rates of solute migration in groundwater at the Richmond site, screening level modelling was performed using a mathematical solute transport model developed by West et al. (2004). The model is capable of simulating the transport of solute in groundwater through a set of parallel, equally spaced fractures subject to advection, dispersion, sorption, degradation and matrix diffusion. The model is also capable of incorporating a finite width source, a variety of source functions, and different degradation rates for the fractures and rock matrix. The full equation development and solution technique is discussed in West et al. (2004).

The mathematical model was employed to perform a sensitivity analysis surrounding the set of base case parameters listed in Table H.1. The simulations presented in this report assume that the solute of interest does not undergo any sorption or degradation reactions (only advection, dispersion and forward matrix diffusion). In this respect, the model simulations apply only to a conservative solute. Solutes that undergo sorption would exhibit arrival times delayed in time compared to those associated with the conservative solute. Solutes that undergo degradation would exhibit concentrations lower than those associated with the conservative solute. Table H.1 (third column) provides the basis for each of the base case parameters. The base case parameters are intended to represent conditions in the intermediate groundwater flow zone. The free solution diffusion coefficient corresponds to chloride at a groundwater temperature of approximately 10 ^{o}C. All results are portrayed as concentration versus time in a monitoring well located downgradient of the southern edge of the landfill. The base case distance of 300 m represents the approximate distance from the southern edge of the landfill to Beechwood Road. The source concentration in the model was set to 1.0, implying that all results can be scaled to any source concentration of interest. No decay of source concentration was adopted, although the model is capable of incorporating such a source function. The model simulations therefore assume that the landfill would be producing leachate at a fixed source concentration for all simulated time periods of interest.

Table H.1 – Base case mathematical modelling parameters.

Parameter	Value	Comment
Source Width (m)	250	Approximately half the width of the landfill.
Source Concentration (-)	1.0	Normalized source concentration.
Fracture Aperture (microns)	68	Average based on hydraulic testing results.
Fracture Spacing (m)	1.78	Average assuming at least one fracture per hydraulic test interval.
Hydraulic Gradient (-)	0.0067	Based on 2008 and 2009 water level data south of landfill.
Distance to Monitoring Well (m)	300	Approximate distance from south edge of landfill to Beechwood Road.
Longitudinal Dispersivity (m)	30	Ten percent of plume length.
Horizontal Transverse Dispersivity (m)	3	Ten percent of longitudinal dispersivity.
Matrix Porosity (-)	0.006	Average of nine measured values.
Matrix Dry Bulk Density (g/cc)	2.69	Average of nine measured values.
Fraction Organic Carbon (-)	0.0	No sorption.
Free Solution Diffusion Coefficient (cm^2/s)	1.89E-05	Wilke and Chang (1955)
Matrix Tortuosity (-)	0.1	Estimate.
Degradation Decay Constant (1/s)	0.0	No degradation.

Figure H.1 presents a plot of concentration versus time in the downgradient monitoring well for the base case simulation as well as a range of distances to the monitoring well of interest. The figure shows that for the base case distance (L = 300 m) it requires approximately five years for 10% of the source concentration to be detected at the downgradient monitoring well. Monitoring wells located closer to the source experience quicker breakthrough, but it requires greater than 200 years for any of the monitoring wells to exhibit solute concentrations approaching that of the source.

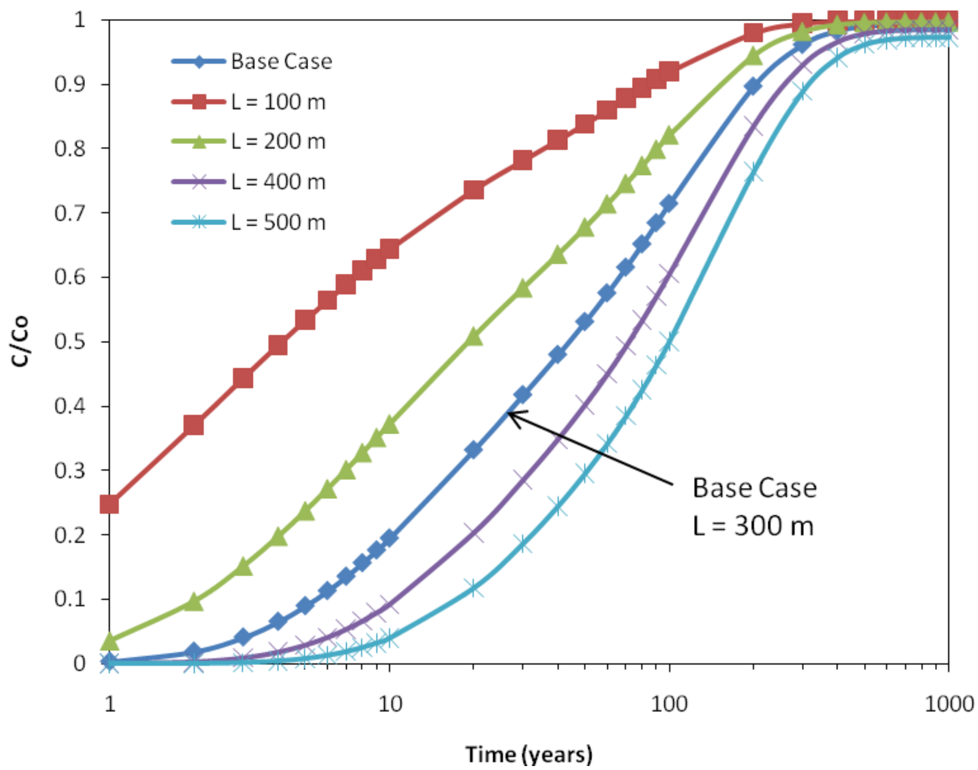

Figure H.1 – Concentration versus time in downgradient monitoring well for the base case simulation and a range of distances to the monitoring well.

Figure H.2 presents a plot of concentration versus time in the downgradient monitoring well for the base case simulation as well as a range of source widths. All of the presented breakthrough curves apply to a monitoring well located 300m downgradient of the source. The source widths range from 10 m to 400 m. The figure illustrates that narrower source widths result in lower concentrations detected at the downgradient monitoring well. This stems from the fact that narrower sources are influenced significantly by transverse dispersion in the fractures, which is an attenuation (dilution) mechanism. Figure H.2 also illustrates that there is relatively no influence of source width for widths in excess of approximately 200 m. It requires greater than 200 years for any of the simulations to exhibit solute concentrations in the monitoring well approaching that of the source concentration.

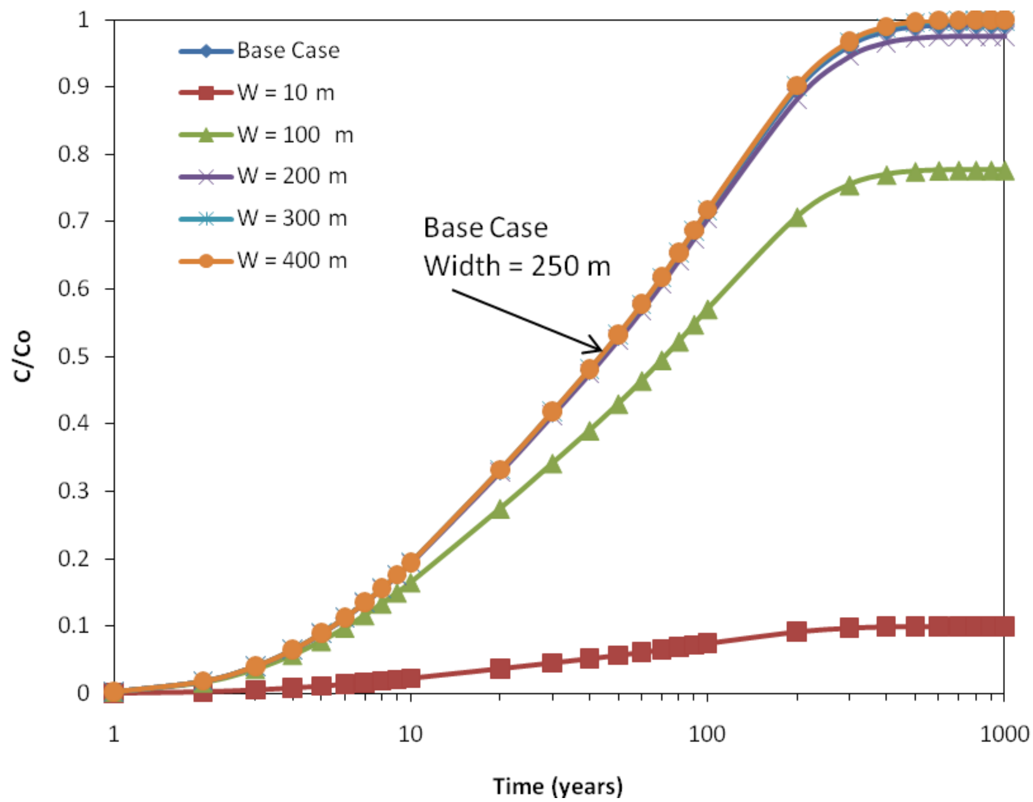

Figure H.2 – Concentration versus time in downgradient monitoring well (L = 300 m) for the base case simulation and a range of source widths.

Figure H.3 presents a plot of concentration versus time in the downgradient monitoring well (L = 300 m) for the base case simulation and a range of longitudinal dispersivity values. In all cases, the transverse dispersivity value was set to 10% of the longitudinal dispersivity value. Figure H.3 illustrates that higher dispersivity values result in faster first arrival times at the downgradient monitoring well, but longer times to achieve the maximum concentration. Overall, the differences between the various breakthrough curves are slight, indicating that the system is not very sensitive to fracture dispersivity. In all cases it requires in excess of 200 years for any of the simulations to exhibit solute concentrations in the monitoring well approaching that of the source concentration.

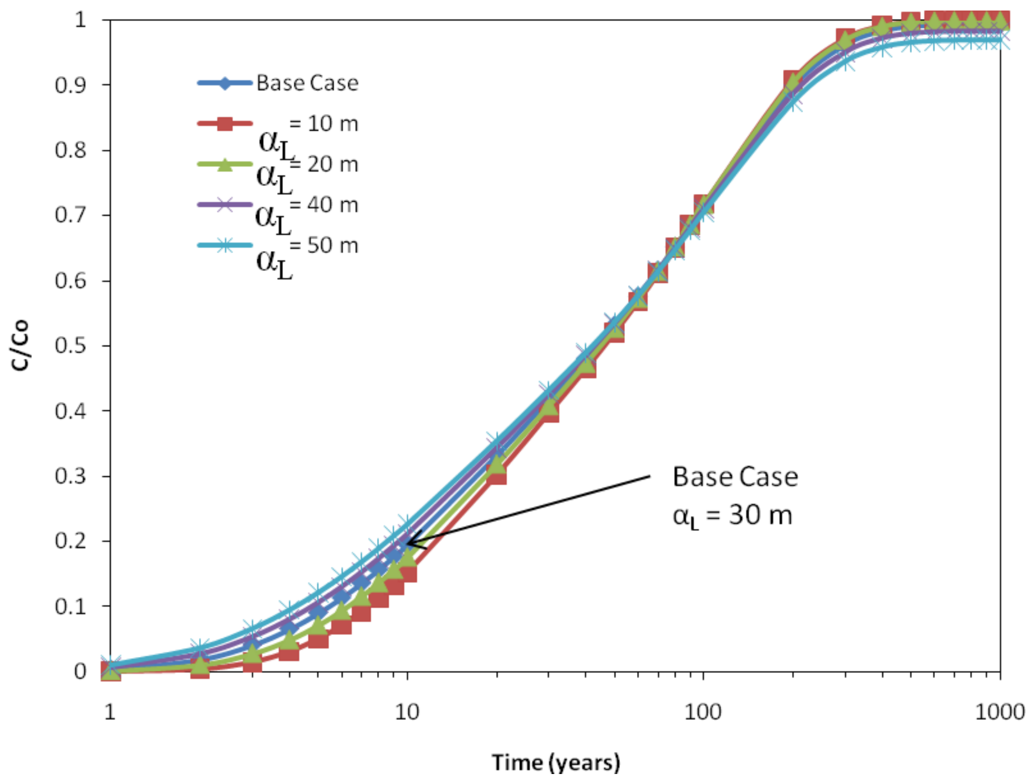

Figure H.3 – Concentration versus time in downgradient monitoring well (L = 300 m) for the base case simulation and a range of longitudinal dispersivity values.

Figure H.4 presents a plot of solute concentration versus time in the downgradient monitoring well (L = 300 m) for the base case simulation and a variety of fracture spacings. The base case fracture spacing (S = 1.78 m) was arrived at by inspecting boring logs and noting how many fractures were present within each interval subjected to hydraulic testing. In cases where no fractures were noted, or a detailed fracture log was not available, one fracture was assumed to be present. This procedure was followed to arrive at the hydraulic apertures presented in Figure 3.11 and to arrive at the average hydraulic aperture of 68 microns adopted by the base case simulation. Figure H.4 illustrates that smaller fracture spacing leads to quicker arrival in the downgradient monitoring well, but in all cases considered it requires in excess of 200 years for the source concentration to be realized in the downgradient monitoring well.

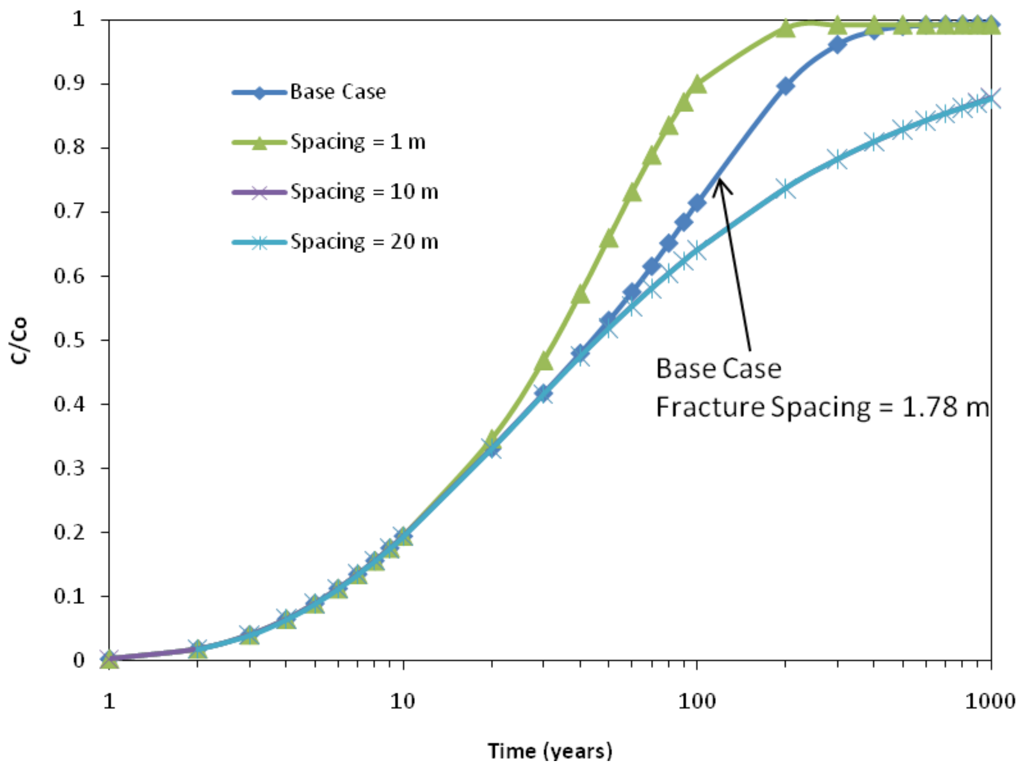

Figure H.4 – Concentration versus time in downgradient monitoring well (L = 300 m) for the base case simulation and a range of fracture spacings.

Figure H.5 presents a plot of solute concentration versus time in the downgradient monitoring well (L = 300 m) for the base case simulation and a variety of fracture apertures. The figure illustrates that first arrival times at the monitoring well are relatively sensitive to fracture aperture, which is not surprising given the fact that groundwater velocity varies with the square of the aperture. In all cases considered, however, there is a gradual build-up of concentration with time and peak concentrations are not realized in any of the simulations until in excess of 200 years. The largest fracture aperture considered in the sensitivity analysis was 100 microns. As discussed in Section 3.2.3.3 of this report, there are relatively few fractures with apertures greater than 100 microns and the majority have apertures less than 50 microns.

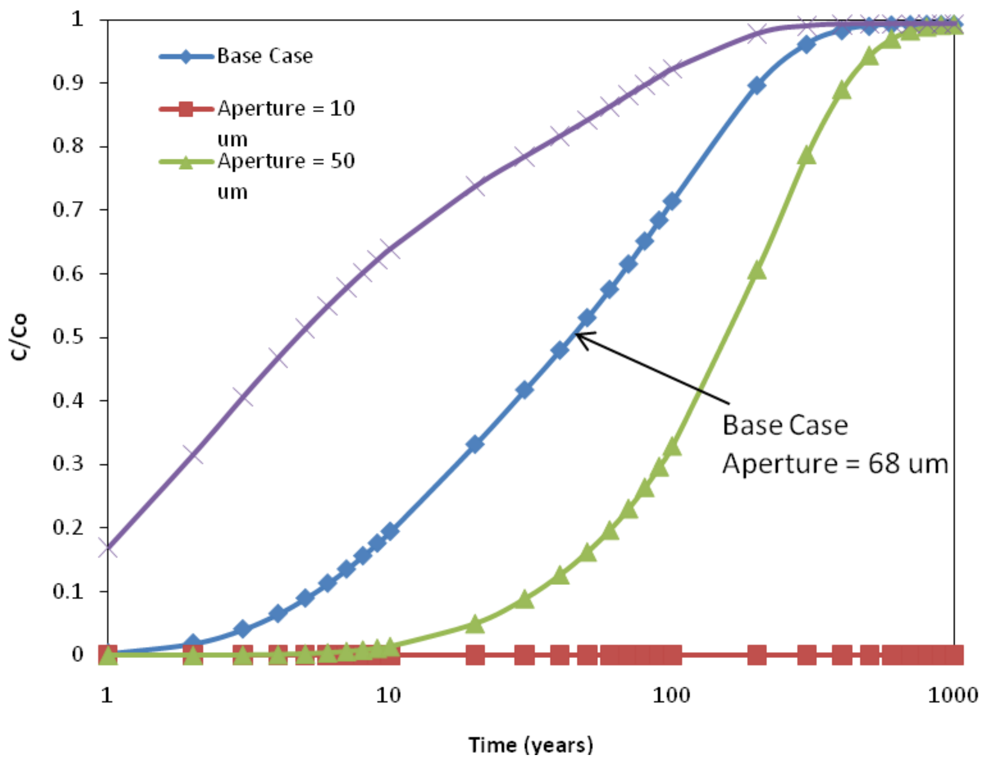

Figure H.5 – Concentration versus time in downgradient monitoring well (L = 300 m) for the base case simulation and a range of fracture apertures.

Figure H.6 presents a plot of solute concentration versus time in the downgradient monitoring well (L = 300 m) for the base case simulation and a variety of matrix porosity values. The figure illustrates that larger matrix porosity values result in later first arrival times at the downgradient monitoring well. The considered matrix porosity values range from 0.005 to 1.0 and result in the arrival of 10% of the source concentration (C/Co = 0.1) at the downgradient monitoring well at times ranging from approximately 4 years (matrix porosity = 0.005) to approximately 12 years (matrix porosity = 0.01). This illustrates that although the matrix porosity values are low compared to some carbonate rocks in Ontario, the forward diffusion process does have a noticeable influence on solute transport times.

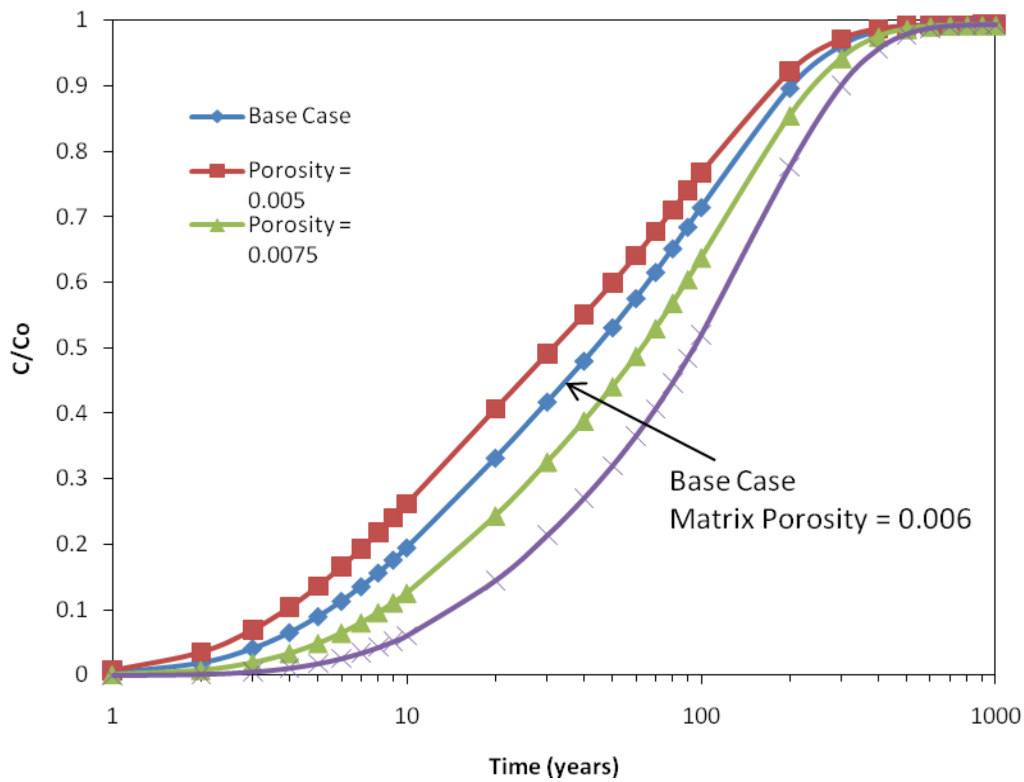

Figure H.6 – Concentration versus time in downgradient monitoring well (L = 300 m) for the base case simulation and a range of matrix porosity values.

The overall conclusion to be drawn from the mathematical modelling presented here is that advection, dispersion and forward matrix diffusion result in a gradual build-up of solute concentration in a downgradient monitoring well. The base case parameters resulted in ten percent of the source concentration arriving at the downgradient monitoring well (x = 300 m) in approximately ten years and 100% of the source concentration arriving in approximately 200 years. The implication of this is that one criteria that could be considered (in conjunction with others) to determine whether a plume is moving through bedrock at the Richmond site is time trend analysis of regular monitoring results. The mathematical model results also illustrate that narrower sources result in lower downgradient concentrations and that solute transport is slower for cases of smaller fracture aperture and larger matrix porosity.