The modelling of a natural diffusion profile and the implications for landfill design

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ABSTRACT

A 10 000-12 000 year old natural diffusion profile which extends from bedrock up through a thick clay deposit is examined. The paper reviews the geological and hydrogeological setting, discusses the modelling and presents the implications of the concentration profile on the interpretation of vertical gradient and hydraulic conductivity at the site. The impact of a landfill constructed on this deposit is then predicted. Particular attention is directed at the interaction between the chloride concentration profile emanating from the bedrock and that derived from the landfill.

1. INTRODUCTION

The prediction of the effects of a proposed landfill site involves an assessment of contaminant migration in the groundwater flow system. In the Province of Ontario, Canada, the Ministry of Environment (MoE) allows one to quantify the extent to which the concentration of a given chemical species in groundwater can be increased by the construction of a landfill. The methodology is outlined in an MoE Policy termed the "Reasonable Use of Groundwater Policy" (MoE Policy 15-08). In the case of chemical species such as chloride, an increase of less than one half the difference between the drinking water objective and the current background concentration is deemed acceptable. However, if the background concentration exceeds the drinking water objective, then no additional chloride may be added to the groundwater. This poses an interesting problem when the water already contains chloride concentrations similar to, or greater than, that typically encountered in landfill leachate.

The present paper examines this problem from two perspectives. Firstly, it documents a natural chloride diffusion profile that has been established over a period of 10 000 to 12 000 years. Secondly, it examines the potential impact of a proposed landfill expansion on groundwater in the underlying aquifer.

2. GEOLOGIC AND HYDROGEOLOGIC SETTING

The study site is located in Southern Ontario, Canada. The clay overburden at the site is between 34 and 39 m thick. The bedrock is the Upper Silurian aged...
Salina Formation which is comprised of soft, erodible shales with evaporites (gypsum) and harder dolostone layers. The bedrock is fractured. Field hydraulic conductivity testing yielded values of between 3.9x10^-2 cm/s and 1x10^-4 cm/s. This range illustrates the effect of intersecting (or not intersecting) hydraulically significant fractures when assessing the hydraulic conductivity of fractured media. The potentiometric surface in the bedrock aquifer suggests a horizontal gradient of about 0.003.

The only aquifer in the study area is the local bedrock. The clay overburden has very low hydraulic conductivity. Hence water wells completed in the overburden do not produce sufficient water to satisfy domestic needs.

In the bedrock aquifer, water quality is generally poor. Chloride, sulphate and sodium levels are typically high. The water can be salty tasting and often has a sulphurous odour. The taste and odour are probably a result of the mineralization and dissolved hydrogen sulphide gas in the water. Wells completed in this unit do, however, satisfy domestic needs.

The overburden sequence is the result of glacial activity that took place in the Late Wisconsin sub-stage of the Pleistocene epoch (23 000 to 10 000 years before present). This period of glacial history was marked by the repeated advance and melting of extensive ice sheets. At the time when the glaciers had reached their maximum extent, deposits of glacial till were being laid down on the bedrock surface. The material, known as the Halton Till (Feenstra, 1981), had a variable silt to clayey silt composition and a low stone content. At the study site, the till-like soils were noted above the bedrock; however, their occurrence and thickness were not uniform. It is interpreted that these till-like soils are the Halton Till.

Overlying this till is a younger and finer grained glaciolacustrine deposit. The glaciolacustrines are primarily silts and clays deposited in various glacial lake phases following the recession of the ice from the area. Radiocarbon dates of 12 000 to 13 000 years B.P. have been reported by Fullerton (1980) and Lewis (1969) for sediments deposited by glacial Lake Warren, the source of the extensive glaciolacustrine clay unit at the site.

Field slug tests indicate that the horizontal hydraulic conductivity of the glaciolacustrine soil ranges from about 4x10^-7 cm/s to 2x10^-7 cm/s. Data from available laboratory tests give vertical (triaxial) hydraulic conductivities between 1.6x10^-4 cm/s and 3.6x10^-4 cm/s. The laboratory consolidation test indicates that for the vertical stress range of 100-200 kPa and 200-400 kPa, the hydraulic conductivities are 3.6x10^-8 cm/s and 1.9x10^-8 cm/s respectively. Based on field measurements in nested observation wells, the vertical gradient through the overburden is about 0.13. Using this gradient, and vertical hydraulic conductivities of 1x10^-4 cm/s and 4x10^-4 cm/s, the downward Darcy flux is calculated to range from 0.0004 to 0.0016 m/a.

Laboratory tests gave a dry density for the clay of approximately 1.2 t/m³ and an organic carbon content of between 0.5% and 0.77%. The chloride diffusion coefficient obtained from two diffusion tests is about 0.012 m²/a. This is somewhat lower than value of about 0.018 m²/a obtained at other locations in Southern Ontario. For the purpose of this study, consideration was given to both the value from the site.
Figure 1. Modelling of Existing Diffusion Profile Over 10 000 Year Period.

The chemistry of water sampled from the overburden monitors and pore water chemistry indicate that there is a chloride concentration profile emanating from the bedrock as shown in Figure 1. This profile has been established based on the chemistry of groundwater from monitoring nests (at locations denoted OW1, OW2, OW3 and OW7) and from the chemistry of porewater squeezed from samples of clay from two of these locations (OW2 and OW7). The data from the groundwater monitors is plotted as bars/boxes which show the length of the monitor and the range of concentrations that have been obtained. The porewater concentrations are plotted...
as point values. It should be noted that position is shown relative to the top of the aquifer since it is this distance that controls the diffusion profile from the bedrock.

3. METHOD OF ANALYSIS

The migration of chloride from the bedrock as well as the proposed landfill was modelled using the finite layer contaminant transport programme (POLLUTE) described by Rowe and Booker (1985; 1987). This approach readily allows the modelling of the existing diffusion profile. The concentration profile is then stored and used as initial conditions for modelling the proposed landfill. As will be discussed, a number of boundary conditions were examined and a reasonable domain was selected for the site assessment.

4. MODELLING OF THE EXISTING DIFFUSION PROFILE

Chloride is a typical tracer used in impact assessments because it occurs in relatively high concentrations in landfill leachate and is stable (i.e. does not undergo sorption or decay). To assess the potential impact of landfill derived chloride on the bedrock aquifer it is essential to consider the natural profile which (despite the passage of about at least 10 000 years) still does not appear to have reached steady state. The details of what has happened in the bedrock over the past 10 000-20 000 years are unknown. Thus one of the challenges associated with modelling the existing diffusion profile is modelling the source conditions in the bedrock. The primary objective in modelling the existing chloride profile is to establish an "initial condition" for use in predicting the effects of the proposed landfill expansion. The initial chloride concentration in the glacio-lacustrine clay was taken as 50 mg/L immediately after deposition (unless otherwise noted). The diffusion profile was then modelled over the subsequent period to present time. The profile was modelled for both 10 000 and 12 000 years to assess the significance of uncertainty concerning the period that has elapsed since deposition.

Recognizing the uncertainties associated with the bedrock history, two strategies were adopted for modelling source conditions in the bedrock. In the first case (Infinite Source), it was assumed that the mass of chloride in the bedrock at a depth of 3 m (i.e. below the most fractured zone) was very large. Therefore, it was sufficient to maintain the chloride level at the bottom of the 3 m fractured bedrock zone at a constant value of 1421 mg/L over the past 10 000-12 000 years (which is a relatively short time in terms of the geologic age of the bedrock unit).

In the second case (Finite Source), it was assumed that the concentration in the bedrock corresponds to a typical value for saline rock and had decayed, over the past 10 000-12 000 years, to the existing average concentration. The mass of chloride in the 3 m fractured bedrock zone was selected such that after 10 000-12 000 years of decay it would correspond to present values. These two extremes are considered to bracket the real situation.

The clay surface was assumed to be washed by surface water which removed
excess chloride. This was achieved using a finite source boundary condition at the top (Rowe & Booker, 1987) where the rate of washing was selected to give general agreement with the pore water squeeze chemistry near the top of the deposit.

Figure 1 shows the calculated diffusion profile at 10,000 years based on these two boundary conditions assuming a diffusion coefficient of 0.018 m²/a and a downward advective (Darcy) velocity of 0.0004 m/a. The diffusion profile calculated in each case is essentially the same. In Case 1 (Infinite Source) the chloride concentration was selected to accord with present conditions while in Case 2 (Finite Source) the mass of chloride was selected so that the concentration in the bedrock closely matches present conditions. Although both approaches give a similar present concentration profile, the different assumptions will result in quite different predictions of future concentrations in the bedrock. Specifically, the calculated chloride concentration in the bedrock will decrease much faster with subsequent time for the finite source than for the infinite source.
The calculated diffusion profile agrees quite well with that observed. While this is partly because the boundary condition at the base was adjusted to match currently observed concentrations in the bedrock, generally good agreement indicates that the basic features of the problem have been correctly modelled.

Figure 2 shows the sensitivity of the calculated concentration profile to the choice of soil diffusion/advection parameters and the elapsed time for the infinite source case. Curves 1 and 2 correspond to the same diffusion coefficient and Darcy velocity as that adopted for the curves in Figure 1. Curve 2 (10 000 years) is in fact identical to the "Infinite Source" curve shown in Figure 1. Comparison of these two curves shows that while the uncertainty regarding elapsed time (from 10 000 to 12 000 years) does result in some variation in the concentrations above the bedrock, the change is not particularly large and the overall characteristics of the diffusion profile are the same for both elapsed times.

Comparison of curves 1 and 3 shows the effect of the range of uncertainty regarding diffusion coefficients. As might be expected, the lower diffusion coefficient (0.0012 m²/a; curve 3) gave rise to smaller concentrations at all points except at the top of the clay and bottom of the fractured bedrock layer (where the concentrations were forced to be the same by the boundary conditions). Both curves fit within the scatter of the data, although it could be argued that curve 1 provides the better general fit.

Even a small downward advective (Darcy) velocity can have a significant effect on the diffusion profile. Curves 1 to 3 were derived assuming a very small downward velocity of 0.0004 m/a based on a gradient of 0.13 and bulk vertical hydraulic conductivity of 1x10⁻⁶ cm/s. If the bulk vertical hydraulic conductivity was 4x10⁻⁶ cm/s, the corresponding downward Darcy velocity would be 0.0016 m/a. While this is still a very small velocity, the effect on the diffusion profile is quite significant. These effects are readily seen by comparing curves 3 and 4. It is evident that curve 4 gives a relatively poor fit to the available field data and observed diffusion profile. Thus the average downward Darcy velocity over the past 12 000 years is likely to have been less than 0.0016 m/a, suggesting that either the bulk hydraulic conductivity is likely closer to 1x10⁻⁶ cm/s than 4x10⁻⁶ cm/s or the vertical gradient has averaged substantially less than 0.13 over most of the past 10 000-12 000 years.

There is some evidence from the field data that the "surface washing" is having some effect on the diffusion profile. For example, the clay is thinnest at OW7 (about 34 m). It can be seen that the pore water concentrations between 22-32 m above the bedrock are consistently less than those obtained at OW2 where the clay deposit is thickest (39 m) and the distance to the washing surface is greatest. One could obtain a slightly better fit by modelling each borehole separately; however, in this study emphasis was placed on the data from OW7 because there was both more data and because the location of OW7 was most critical for the purpose of assessing potential landfill impacts on the aquifer.

Notwithstanding the data scatter, it is evident that the concentration profile is the result of long term (10 000-12 000 years) upward diffusion from the bedrock in the presence of very small downward flow and that the observed diffusion profile can be reasonably predicted.
5. MODELLING OF POTENTIAL IMPACT

Based on existing information, the design or expected input chloride concentration is 560 mg/L. Calculations were also performed for a "worst case" leachate with a chloride concentration of 1500 mg/L and these are the results reported herein.

For the purpose of modelling the potential impact on groundwater, the mass of contaminant within a landfill was represented in terms of a "reference height of leachate", \( H_r \), of 5.85 m (see Rowe, 1991; Rowe & Booker, 1990a). This depends on the mass of waste and the initial (reference) contaminant concentration, \( c_0 \). After considering potential leachate mounding in the landfill, the "worst case" Darcy velocity for downward movement of contaminant from the landfill is taken to be 0.0043 m/a.
Figure 3 shows the calculated concentration profile beneath the proposed landfill at times of 10, 50, 100, 250 and 500 years after present (i.e. 10 010, 10 050, 10 100, 10 250 and 10 500 since the start of the modelling period). The profiles are based on the "finite source" boundary conditions and the chloride concentration profile for "Finite Source" (Figure 1) at the time just prior to construction of the landfill.

It can be seen that there is a chloride plume from the landfill that starts to move down towards the bedrock. As the plume moves down, the concentration decreases with distance from the source (landfill). The concentration in the landfill also decreases with time as a result of contaminant removal by the leachate collection system (see Rowe, 1991 for a more detailed discussion). In this case the landfill is quite small and with an infiltration of 0.15 m/a the chloride concentration decreases to less than 10% of the initial source value within about 100 years. Eventually chloride that had originated in the landfill reaches a depth (about 7 m in this case) where its further downward movement is countered by the upward diffusion of chloride from the bedrock. The landfill chloride then begins to migrate back up toward the landfill, since by this time, the leachate concentration in the landfill has decayed to the point that it is substantially less than the concentration in the underlying soil. As a result, there will be no increase in chloride concentration in the bedrock aquifer due to the landfill.

The case examined in Figure 3 adopted a finite source boundary condition which matched the observed concentration in the bedrock based on 10 000 years decay in the bedrock. This decay continues with additional time after the landfill construction as can (Figure 3) and represents the "worst case" for potential contaminant impact. The "infinite source" boundary condition was also examined and, as might be expected, the results immediately beneath the landfill are identical to those presented in Figure 3 (to plotting accuracy) while the concentration at the bottom remains much closer to current values (and remains constant at the bottom of the 3 m of fractured rock). The potential for impact on the aquifer is less in this case because a stronger upward diffusion gradient is maintained for time subsequent to construction of the proposed landfill.

6. CONCLUSION

An existing diffusion profile established over a period of about 10 000 - 12 000 years (since the last retreat of glaciers from Southern Ontario) has been examined and found to be readily explained based on the data derived from field studies. The impact of a landfill on chloride concentrations in the aquifer was then examined and it was found that the concentration plume from the landfill met, and was pushed back, by the concentration gradient emanating from the bedrock aquifer.

The data and analyses presented in this paper serve to demonstrate the long term significance of molecular diffusion as a contaminant transport mechanism. It also demonstrates that the 10 000 to 12 000 year old diffusion profile is consistent with predictions based on laboratory test results that can be derived over a period of days.
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