Waste Disposal Facility Site Selection and Design Considerations

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SUMMARY

Considerations associated with the selection and design of a suitable waste disposal facility are discussed. These considerations include the potential for protection of groundwater quality, predictability of groundwater movement, and potential for disruption of groundwater users. In the design of a waste disposal facility engineered systems are often incorporated, and the service life of these systems must be considered when assessing their potential impact. The role of modelling in predicting the potential impacts due to the interaction between the hydrogeology and the proposed engineering is discussed. The potential impact of different landfill designs on groundwater quality is examined for a hypothetical.

INTRODUCTION

The selection of a suitable site and design for a waste disposal facility such as a landfill, involves the interaction of many disciplines. Even within the geoscience area there is often need for the coordinated consideration of geology, geophysics, geochemistry, hydrogeology, geotechnical engineering and landfill design in order to characterize a particular site and then develop an appropriate engineered facility for that site. It is necessary to have an adequate understanding of both the existing site conditions and an understanding of how the proposed facility will affect the existing conditions both in the short term and in the long term. In this context, the potential short term impacts may extend for up to several decades (eg. during landfill construction) while the potential long term impacts may extend over periods of up to several centuries. This latter period of time, during which a landfill will produce contaminants at levels that could have unacceptable impact if they were discharged into the surrounding environment, is often called the "contaminating lifespan" of the landfill. The contaminating lifespan may depend on a number of factors including the natural setting (eg. site geology and hydrogeology), landfill size, nature of the waste, climate and landfill design. There are a number of important geo-factors to be considered in the selection of a suitable site as discussed below:

Potential for Protection of Groundwater Quality

An assessment of the potential for protecting groundwater quality from degradation due to the migration of contaminants from the landfill may involve consideration of natural geologic protection, hydraulic protection and engineered systems.

Natural geologic protection generally refers to the ability of a geologic feature such as a clay till aquitard to attenuate contaminants as they migrate from the landfill through the aquitard to some potential receptor aquifer (eg. Yanful et al, 1988). This potential for attenuation (i.e., a reduction in concentration of contaminants) will depend on the effective thickness and bulk hydraulic conductivity of the aquitard between the base of the engineered facility and the receptor aquifer. The effective thickness will, of course, depend on the existing thickness of the hydrogeologic unit (i.e., the aquitard) but will also depend on engineering and other environmental constraints that will influence the depth of excavation. Thus, even in this case neither the geology/hydrogeology and the engineered design can be considered in isolation; increasing the depth of excavation may decrease other environmental impacts (eg. traffic, noise, dust, visual impacts etc.) which affect peoples lives in the "short term" (which could be decades as noted above) but this may be traded off against a consequent decrease in natural protection of groundwater quality in the long term. This may then need to be countered by increased engineered protection (such as discussed later in this paper).

The bulk hydraulic conductivity of the aquitard unit will depend on factors such as the density, grainsize distribution and mineralogy of the geologic unit, and may be controlled by the presence of secondary features such as fractures (eg. D'Astous et al, 1989, Herzog et al, 1989). Thus, an important part of the evaluation of the potential impact on groundwater quality is an evaluation of a reasonable value (or, more typically a range of values) for the bulk hydraulic conductivity of any natural attenuation layer.

Hydraulic protection involves the use of natural groundwater levels (usually in the potential receptor aquifer) to induce a small flow into the landfill from the aquifer. Clearly where there is groundwater flow into the landfill, there will not be an outward flow of contaminated water (commonly called "leachate") from the landfill to the aquifer. Also, the inward flow tends to reduce the outward movement of chemicals in the leachate due to the process of molecular diffusion. This concept of hydraulic protection (sometimes called a "hydraulic trap") has gained popularity since the approval of the Halton Waste Management Facility (see Rowe et al, 1993), however, as discussed by Rowe et al. (1994b) it is far simpler in concept than in implementation. In particular it is important to consider not only the existing groundwater levels but also the landfill base elevations; hydraulic conductivity of the aquitard and/or engineered system between the aquifer and the base of the waste; and the transmissivity of the aquifer to assess the effect of landfill construction and operation on water levels in the aquifer and the consequential potential impact on the effectiveness of the "hydraulic trap".

In North America the last decade has seen a major movement from largely uncontrolled disposal of waste in "town dumps" to the controlled disposal of waste in engineered landfills. The level of engineering can vary substantially depending on the natural environment, the size of the landfill, the nature of the waste and local regulations. As a minimum, most modern landfills have some form of engineered final cover over the waste that serves to control the infiltration of water into the waste and the consequent generation of contaminated water (leachate) as well as some form of engineered system for the collection of leachate. Some landfills, such as the Keele Valley Landfill just north of Toronto (King et al, 1993) have an engineered compacted clay liner to control the rate of migration of contaminants, others such as the Halton landfill involve natural hydraulic protection combined with a backup compacted clay liner as an engineered contingency system (Rowe et al, 1993). In the United States composite liners are commonly used. These consist of a layer of plastic (typically 1 mm to 2 mm thick high density polyethylene, HDPE) known as a geomembrane, overlying a compacted clayey liner (eg. see Koerner, 1990; Rowe et al, 1994b). A number of engineered systems will be discussed in the latter section of this paper.

Predictability of Groundwater Movement

It is important that the hydrogeology of a proposed landfill site be sufficiently well understood that it will allow reliable monitoring of the site. In addition, there needs to be some viable contingency measure that can be implemented in the event that some unexpected contamination of groundwater does occur. This requirement for reasonable predictability is more restrictive with respect to what constitutes a suitable natural system than the requirement for protection of groundwater quality since natural protection can be readily supplemented be additional engineering if needed. However, it is generally much more difficult to improve the predictability of a site using engineering.

Potential for Disruption of Groundwater Users

In this context, disruption of groundwater users includes both existing and potential users, particularly when there is no viable alternative water source. It may also involve potential disruption of stream baseflow due to groundwater drawdown.

The potential for disruption may be short term, either due to conventional construction drawdown or the depressurization of an aquifer that may be necessary to construct a "hydraulic trap" landfill. However the potential disruption may also be long term due to the cutoff of groundwater recharge over the area of the landfill causing a drop in water levels, and/or due to a drop in water levels due to the operation of a "hydraulic trap" as discussed earlier.

A less obvious potential for disruption of groundwater users is a degradation in groundwater quality resulting from a change in water levels that induces mixing of unpotable water (eg. saline water in fractured bedrock) with what was originally overlying fresh water. This situation creates two potential problems. Firstly, degradation of water quality is undesirable irrespective of whether it results directly from leachate escaping from the landfill, or indirectly due to mixing of saline or brackish groundwater with overlying fresh water. Secondly, this would complicate monitoring since chloride is one of the most commonly used "critical contaminants" used to identify if there has been an escape of leachate from a landfill. In this situation if would be more difficult to identify whether an increase in chloride concentration was due to upwelling of underlying groundwater or due to leachate escaping from the landfill.

Modelling

Observational techniques may be used to establish existing site conditions. However any prediction of potential impacts often involves modelling which considers the interaction between the hydrogeology and the proposed engineering. The landfill design usually involves an interactive process wherein an initial design proposal is evaluated for its potential impact and then revised, as necessary, to mitigate predicted impacts. For example, in the design of a "hydraulic trap" landfill the engineer can control the base elevations of the landfill, and the further these are below the water levels in the underlying receptor aquifer the greater will be the flow into the landfill (all other things being equal) and hence the better the "hydraulic trap". However, there is a tradeoff between the benefits gained due to an increased groundwater gradient into the landfill and the disadvantages of decreasing the thickness of the attenuation layer between the landfill base and the receptor aquifer. Furthormore, there is an increased potential for disruption to groundwater users due to the volume of groundwater collected, with the consequent changes in local groundwater levels. Alternatively, the engineer may examine different levels of engineering (eg. compacted clay versus composite liners, single verses double liners, etc.) when seeking to mitigate potential impacts.

Modelling will usually take the form of flow modelling and/or contaminant transport modelling. A useful overview of modelling is given by Frind (1987) and a more detailed discussion on its applications to engineered landfills is given by Rowe et al (1994b).

Flow modelling may range from single hand calculation and simple analytical solutions (eg. Rowe and Nadarajah, 1994) to two dimensional cross-sectioned models (eg. Frind and Matanga, 1985) and two dimensional area models (eg. Franz and Guiger, 1989). Three dimensional modelling (eg. Huyakorn et al, 1986) is rarely used since the data base is often not sufficiently detailed to justify the high cost of performing three-dimensional analysis relative to the improvement in understanding that can be obtained. However, there are exceptions to this observation and in some cases three dimensional modelling can give valuable insight (eg. Molson and Frind, 1991; 1993).

Contaminant transport models vary substantially in sophistication and ease of use. A review of a number of commonly used models has been given by Pandit et el (1993.) and Franz (1993), while Panigrahi et al (1993) described the input requirements for many of these models. Franz and Rowe (1993) discuss the application of several models for a particular landfill design situation.

To illustrate some of the considerations associated with the modelling of the potential impact of a landfill on groundwater quality, the following sections illustrate how simple models can be used to quickly evaluate the potential impact of different landfill designs on groundwater quality for a hypothetical case.

Since this impact is a consequence of the interaction between a particular hydrogeology and landfill design, the numerical results presented in this analysis should not be generalized beyond the level discussed in this paper.

The migration of contaminants from the landfill into the aquifer was modelled using a finite-layer analysis model (Rowe and Booker, 1985, 1991, 1994), as implemented in the computer program POLLUTEv6 (Rowe et al, 1994a).

EXAMPLE PROBLEM

In this analysis the local hydrogeology is assumed to consist of a silty clay overlying a gravel and sand aquifer (Figure 1). The silty till is assumed to have a hydraulic conductivity of $1x10^{-8}$ m/s, a porosity of 0.4, and a diffusion coefficient of 0.02 m^2/a.

Beneath the silt till is a confined aquifer consisting of gravel and sand. This aquifer is assumed to be 3 m thick, and have a porosity of 0.35. At the up-gradient edge of the landfill the horizontal flow in the aquifer per unit width is assumed to be 30 $m^3/a/m$ (i.e., a Darcy velocity of 10 m/a). This flow will be increased at the down-gradient edge of the landfill by the downward Darcy flux originating from the landfill. The potentiometric head in the landfill is assumed to be 4 m above the top of the aquifer. The infiltration through the silty landfill cover is assumed to be 0.15 m/a.

To quantify the impact associated with the interaction between the hydrogeology and the landfill design the migration of chloride (a common component in municipal solid waste) was considered. The initial concentration after closure of the landfill was assumed to be 1500 mg/L, and the mass of the chloride was assumed to represent 0.2% of the waste. In this analysis the waste was assumed to have an average thickness of 20 m, and an apparent waste density of 600 kg/m^3. The landfill was assumed to be 1000 m long in the direction of groundwater flow. In assessing the impact of the landfill the mass of contaminant was modelled as described by Rowe (1991a).

SOME LANDFILL DESIGN CONSIDERATIONS

The initial landfill design to be considered, consists a 0.3 m thick granular leachate collection system placed directly on top of the silty clay (Figure 1). In this and subsequent landfill designs it is assumed that the silt till must be excavated such that the base of the leachate collection system is 6 m above the top of the aquifer. This excavation would then allow for the placement of the 20 m thickness of waste.

Leachate is formed when rainwater and runoff percolate through solid waste, leaching out soluble salts and biodegraded organic products. A leachate collection system is typically a granular layer with embedded pipes, used to collect and remove the leachate at the bottom of a landfill. The primary functions of a leachate collection system are to reduce the volume of leachate in the landfill and in particular the pressure exerted by leachate at the base of the landfill. Removal of leachate also reduces the amount of contaminant available for transport into the hydrogeological system. By reducing the volume of leachate at the base of a landfill the height of the leachate mound will be reduced, this will result in a lower hydraulic gradient beneath the landfill and consequently a lower the Darcy velocity out of the landfill into the hydrogeology. In this design it is assumed that the leachate collection system is able to maintain the leachate mound at an average height of 0.3 m above the base of the landfill. The Darcy velocity beneath the landfill would then be 0.12 m/a, which would leave 0.03 m/a (i.e., about 20%) to be collected and removed by the leachate collection system.

Due to the downward Darcy velocity and diffusion, contaminants will migrate from the landfill through the silt till and into the aquifer. As time passes more and more contaminants will migrate into the aquifer at higher and higher concentrations. The contaminant mass in the aquifer will then be transported away from the landfill by the horizontal flow in the aquifer. In this manner the mass of contaminants in the landfill will be continuously depleted as contaminants are either removed by the leachate collection system or migrate downward into the aquifer. Eventually if the source of the contaminants is finite, as in a landfill, the mass of contaminants transported into the aquifer will decline resulting in lower and lower concentrations of contaminants in the aquifer. Thus there will be an initial increase in concentration in the aquifer, followed by a decline in concentration with time, creating a peak concentration in the aquifer.

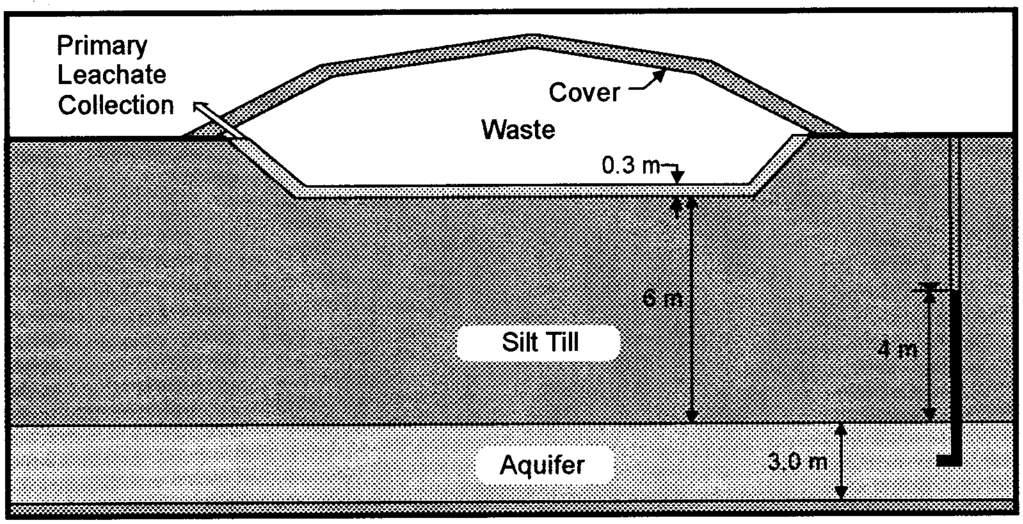

Figure 1. Landfill Design with Leachate Collection System only.

Figure 2 shows the concentration of chloride in the aquifer that results from this landfill design and hydrogeology. The concentration in the aquifer reaches a peak value of about 1000 mg/L at 45 years, and then declines. In Ontario, the Ministry of Environment and Energy 'Reasonable Use' Policy (MOEE Guideline and Procedure B-7, 1994) limits the increase in the concentration of chloride in an aquifer to a maximum of 125 mg/L, assuming that there is negligible background concentration. According to this policy the landfill design would not be acceptable, given the assumed hydrogeology.

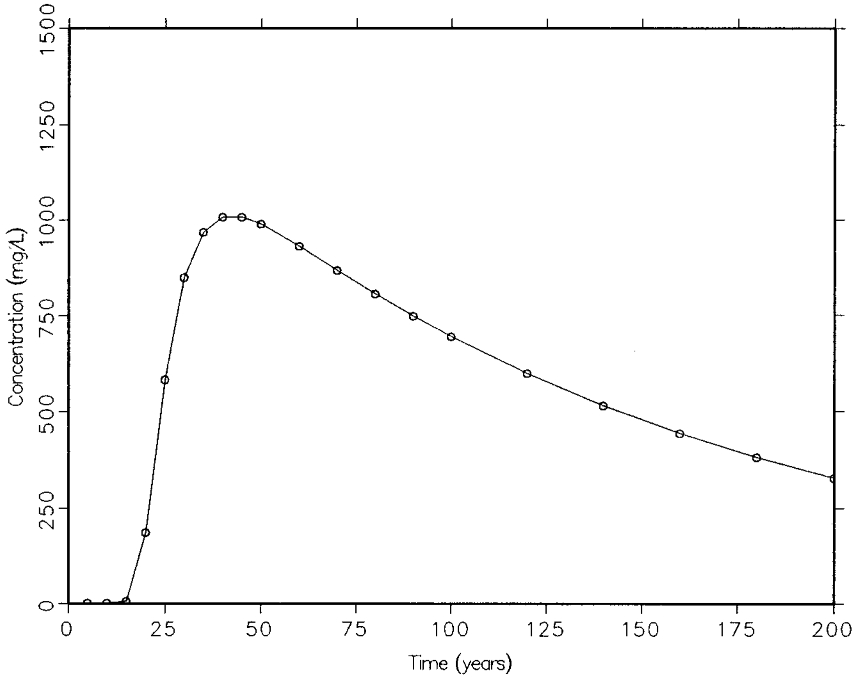

Figure 2. Chloride Concentration in Aquifer.

Add a Clay Liner?

An alternative landfill design that may result in a lower peak chloride concentration in the aquifer, would include a compacted clayey liner beneath the primary leachate collection system. This compacted clayey liner would have a much lower hydraulic conductivity than the silt till, thus reducing the Darcy velocity beneath the landfill. In this analysis the compacted clay liner is assumed to be 1 m thick, have a hydraulic conductivity of $2x10^{-10}$ m/s, a porosity of 0.35, and a diffusion coefficient of 0.02 m^2/a (Figure 3). The resulting Darcy velocity beneath the landfill is now 0.013 m/a, instead of the previous 0.12 m/a. This lower Darcy velocity allows for the leachate collection system to function much more efficiently and collect 0.137 m/a (or about 91% of the leachate generated).

The concentration of chloride in the aquifer that would result from this landfill design is shown in Figure 4. This concentration reaches a maximum value of 133 mg/L at 200 years, which is still above the maximum 125 mg/L allowed by the MOEE Guideline B-7.

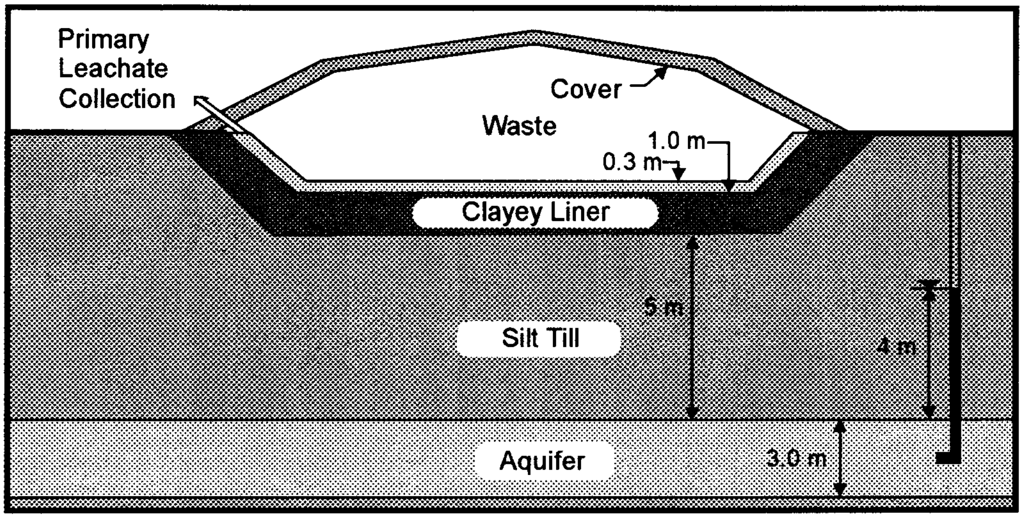

Figure 3. Landfill with Compacted Clay Liner.

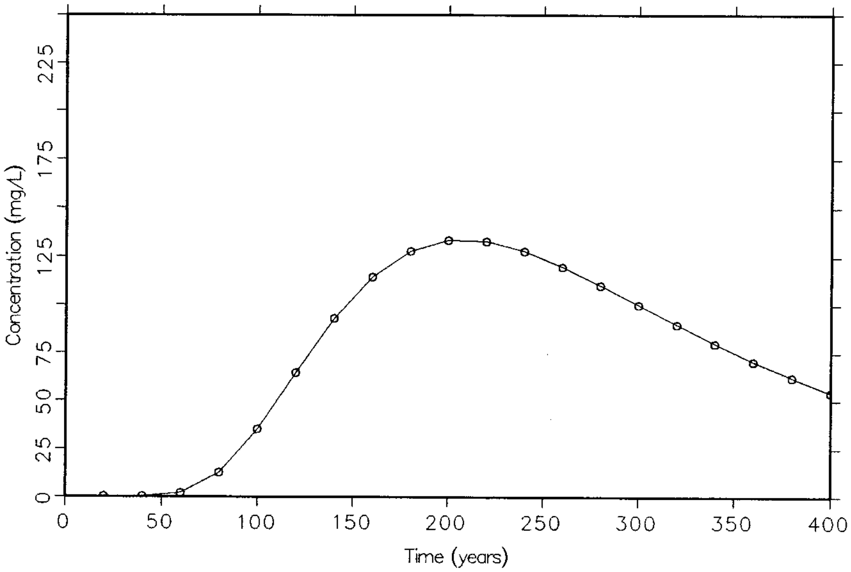

Figure 4. Chloride Concentration in Aquifer for Clay Liner.

Add a Tight Cover?

A possible design change that might be considered is to add a tight cover over the landfill (Figure 5). By adding a tight cover the amount of percolation through the waste is limited, resulting in less leachate being produced each year. This tight cover is assumed to limit the infiltration into the landfill to 0.008 m/a. The maximum Darcy velocity that can occur beneath the landfill is limited to the annual infiltration through the landfill cover, since maximum amount of leachate that can migrate out of a landfill is limited to the amount of leachate that is created. Thus the Darcy velocity beneath the landfill is 0.008 m/a, and the amount of leachate that is collected by the leachate collection system is negligible.

Figure 6 shows the concentration of chloride in the aquifer for a landfill design that incorporates a tight cover. Notice that there is still a significant amount of contaminants reaching the aquifer. These contaminants are primarily transported by the process of molecular diffusion, since the Darcy velocity is low due to the tight cover. In this design the maximum chloride concentration was 190 mg/L at 500 years, which is even higher than that for the design with a permeable cover. By adding a tight cover the peak concentration in the aquifer was delayed by 300 years, since diffusion tends to be a slower process than advection. However, the magnitude of the peak concentration increased since very little contaminant was removed by the leachate collection system.

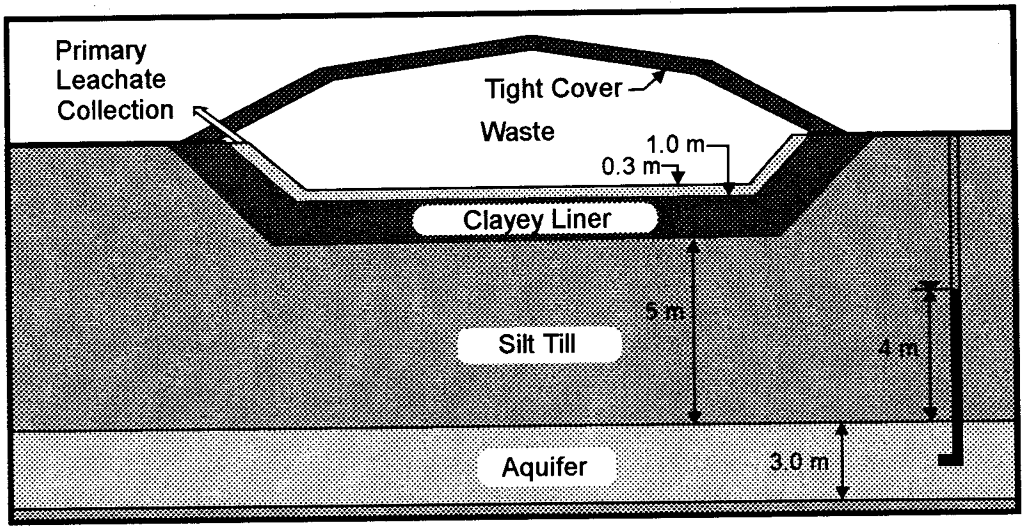

Figure 5. Landfill with Tight Cover.

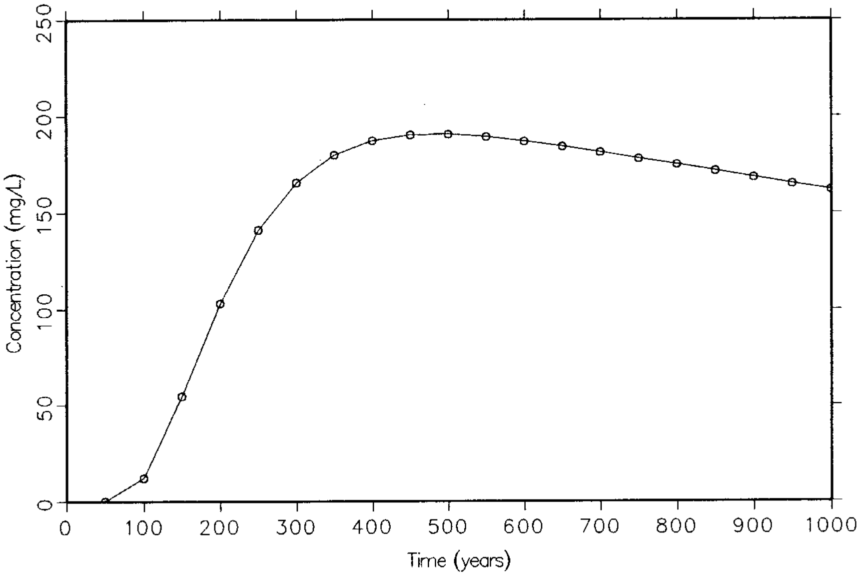

Figure 6. Chloride Concentration in Aquifer for Tight Cover.

Add a Geomembrane Liner?

Another possible design alternative that may reduce the amount of contaminants reaching the aquifer is to add a geomembrane on top of the compacted clay (Figure 7). This type of barrier composed of a geomembrane in good contact with a compacted clayey layer, is called a composite liner. The geomembrane in this design is assumed to be 1.5 mm (60 mil) thick HDPE, and have a diffusion coefficient of $3x10^{-5}$ m^2/a. During the manufacture and installation of a geomembrane small holes or defects may be introduced into the geomembrane. Since intact geomembranes may be virtually impervious, the majority of flow through a geomembrane may be attributed to flow through the small holes.

In this design the geomembrane is assumed to have small defects of 0.1 cm^2 area with a frequency of one every acre (2.5/ha). The effective hydraulic conductivity of the geomembrane is then $1.1x10^{-15}$ m/s, which was backfigured based upon the likely leakage through a "well constructed" composite liner using information from Giroud et al. (1992). The Darcy velocity through the composite liner and silt till would be $5.3x10^{-5}$ m/a. And the volume of leachate that would be collected by the leachate collection system, assuming a permeable cover, would be 0.1499 m/a (i.e., essentially 100%).

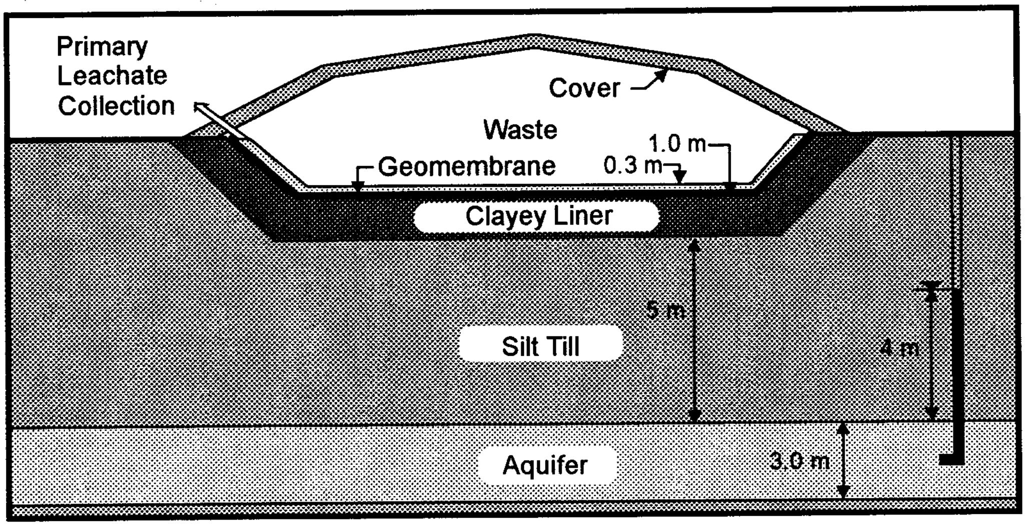

Figure 7. Landfill Design with Composite Liner.

The concentration of chloride in the aquifer that would result from this design, incorporating a composite liner, is shown in Figure 8. A maximum chloride concentration of 14 mg/L occurs at 360 years. This maximum is well below the maximum 125 mg/L specified by the MOEE Guideline B-7.

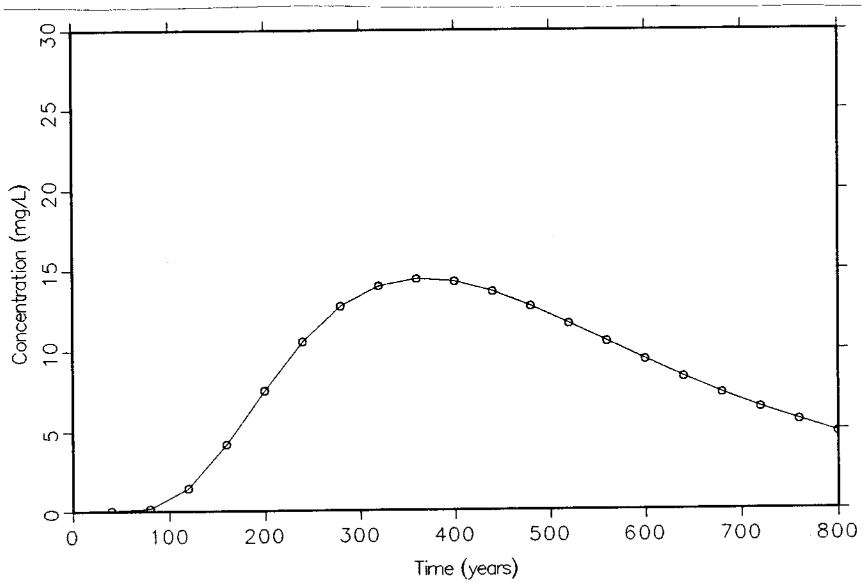

Figure 8. Chloride Concentration in Aquifer for Composite Liner.

What if the Collection System Clogs?

The time period during which an engineered system, such as a leachate collection system, is fully functional is defined as the service life of the engineered system. This service life is unlikely to be infinite and will be highly dependent on the design of the system. For example, leachate collection systems may eventually clog due to chemical and biological activity. If the service life of an engineered system is less than the contaminating lifespan (Rowe 1991a, 1991b) of the landfill, than they may have a substantial effect upon the contaminant impact of the landfill.

While the leachate collection system is functioning, the leachate mound at the base of the landfill is likely to be relatively small, in this design it is assumed to be an average of 0.3 m. If the leachate collection system fails and becomes clogged the leachate mound will increase in height at a rate controlled, inter alia, by the infiltration through the cover and the downward Darcy velocity through the liner. The maximum height of the leachate mound is also controlled by the thickness of the waste, in this analysis assumed to average 25 m. If the leachate mound reaches this maximum height, any excess leachate generated will escape from the landfill via toe drains and seeps through the cover.

The service life of the leachate collection system in this analysis is assumed to be 50 years after closure. After this time the leachate collection system begins to experience significant decreases in performance due to clogging, until at 75 years it is no longer controlling the height of the leachate mound in the landfill (Figure 9).

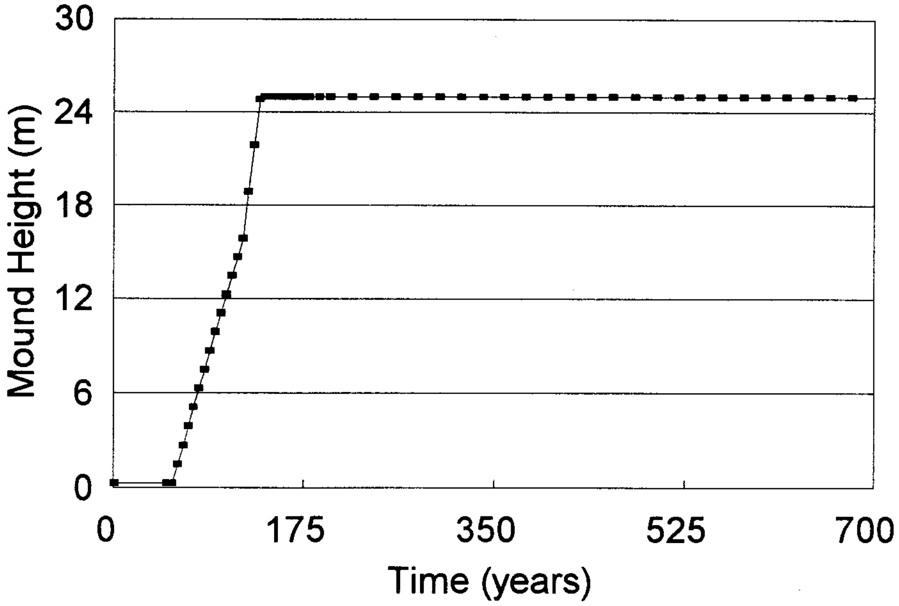

Figure 9. Leachate Mound when Collection System Fails.

In Figure 10 the resulting chloride concentration in the aquifer is shown, assuming the leachate collection system fails. The maximum chloride concentration in the aquifer is 18 mg/L at 340 years, which is only slightly more than it was when the leachate collection system did not fail. Thus, it would appear that the failure of the leachate collection system need not be a major concern in this design, which assumes that the geomembrane has an infinite service life.

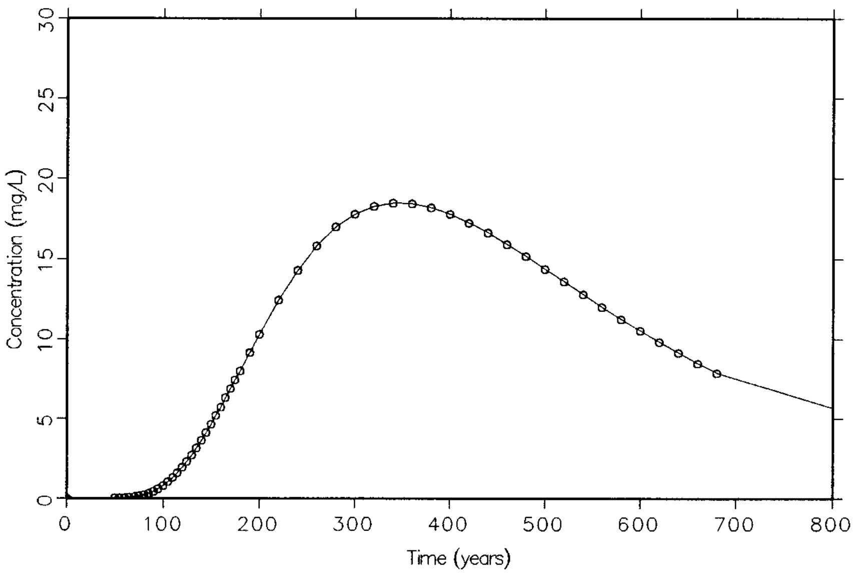

Figure 10. Chloride Concentration in Aquifer for failed Collection System.

What if Geomembrane Degrades?

Geomembranes may also have a limited service life, due to degradation caused by chemical attack and other processes. This degradation will result in an increase in the effective hydraulic conductivity of the geomembrane. In this analysis the geomembrane is assumed to have a service life of 125 years, after which it will begin to significantly degrade, until at 150 years it is no longer having an impact upon the Darcy velocity beneath the landfill. The Darcy velocity beneath the landfill will initially be relatively small due to the presence of the geomembrane, however as the geomembrane degrades this velocity will start to increase until it reaches a maximum value which is assumed to be that of the compacted clay beneath the geomembrane.

These changes in Darcy velocity will have an effect upon the height of the leachate mound. Initially the height of the leachate mound will be 0.3 m while both the leachate collection system and geomembrane are functioning. After the leachate collection system fails this mound will increase to its maximum height, where it will stabilize until the geomembrane fails. When the geomembrane fails the leachate mound may decrease in height due to the increased Darcy velocity through the landfill liner. Eventually the leachate mound will stabilize at a new height that in controlled by the Darcy velocity through the liner and the infiltration through the cover (Figure 11).

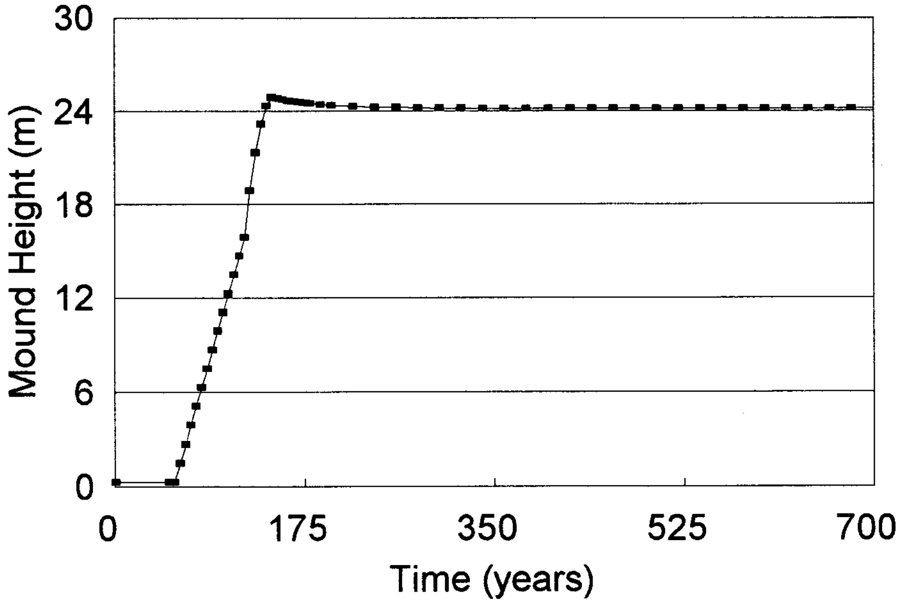

Figure 11. Leachate Mound when Collection System and Geomembrane Fail.

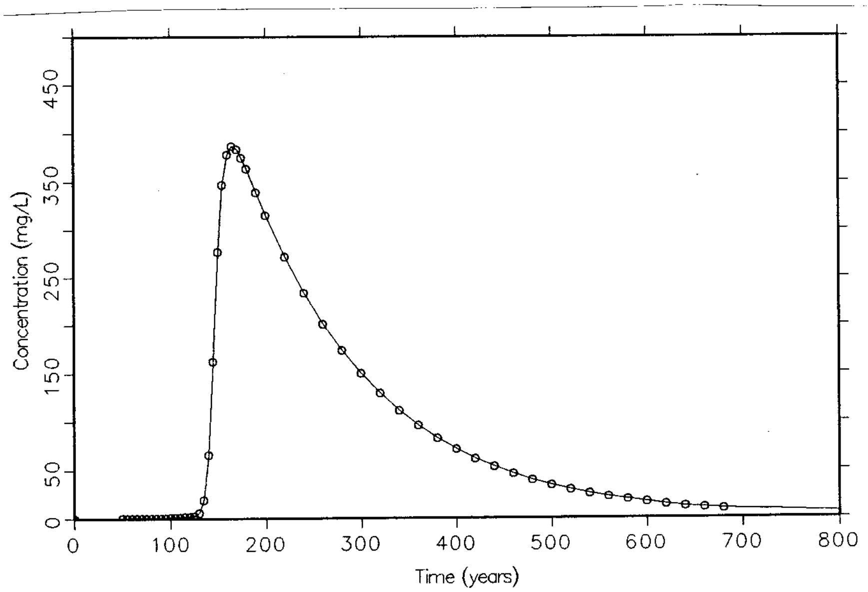

Figure 12. Chloride Concentration in Aquifer for failed Collection System and Geomembrane.

The calculated chloride concentration in the aquifer is shown in Figure 12, for this design assuming finite service lives of the leachate collection system and geomembrane. Based upon these assumptions the maximum chloride concentration in the aquifer is 387 mg/L at 165 years, which would not be acceptable according to the MOEE Guideline B-7. At this stage it would be necessary to further refine the design of the landfill to achieve a contaminant impact that is acceptable according to the MOEE policy. These refinements may include:

- addition of a secondary leachate collection system and liner,
- use of a lower permeability compacted clay liner,
- changes in the base elevation of the landfill and/or
- control of the leachate mound after failure of the leachate underdrain system.

CONCLUSIONS

This paper has attempted to summarize some of the considerations associated with the selection and design of a suitable waste disposal site. Irrespective of how much engineering is proposed, it is important to have an adequate understanding of the site geology and hydrogeology to allow confident monitoring of the site and the development of reasonable contingency measures that could be used to mitigate any unexpected escape of leachate from the facility. Thus, the engineered design does not reduce the need for an adequate hydrogeologic investigation. However, the reality is that most modern landfills will require some form of engineering and the interaction between this engineering and the natural system also needs to be considered. This is usually achieved by means of flow and/or contaminant transport modelling.

The evaluation of potential impacts of a proposed facility on groundwater quality or quantity usually requires consideration of reasonable uncertainty regarding both the natural system (eg. the hydraulic conductivity of aquitards and aquifers) and the engineered systems. As illustrated in this paper an unacceptable potential impact that might arrive from simply using natural attenuation can be mitigated by the appropriate selection of engineered leachate control systems. However, in the case of engineered systems, consideration should also be given to the service life of the components of this system and the implications that this may have on potential impact.

REFERENCES

D'Astous, A.Y., Ruland, W.W., Bruce, J.R.G. et al. 1989. Fracture effects in the shallow groundwater zone in weathered Sarnia-area clay. Canadian Geotechnical Journal, 26 (1), pp. 43-56.

Franz, T. 1993. Hydrogeological computer models used in evaluating contaminant transport. Geotechnical News, 11 (4), pp. 50-52.

Franz, T. and Guiguer, N. 1989. FLOWPATH: Steady-State Two-Dimensional Aquifer Simulation Model. Waterloo Hydrogeologic Software, Waterloo, Ontario, Canada.

Franz, T. and Rowe, R.K. 1993. Simulation of groundwater flow and contaminant transport at a landfill site using models. International Journal for Numerical and Analytical Methods in Geomechanics, 17, pp. 435-455.

Frind, E.O. 1987. Modelling of contaminant transport in groundwater. An overview, in The Canadian Society for Civil Engineering Centennial Symposium on Management of Waste Contamination of Groundwater, Montreal, May. 35 pp.

Frind, E.O. and Matanga, G.B. 1985. The dual formulation of flow for contaminant transport modelling 1. Review of theory and accuracy aspects. Water Resources Res., 21 (2), pp. 159-169.

Giroud, J.P., Badu-Tweneboah, K. and Bonaparte, R. 1992. Rate of leakage through a composite liner due to geomembrane defects. Geotextiles and Geomembranes, 11, pp. 1-19.

Herzog, B.L., Griffin, R.A., Stohr, C.J. et al. 1989. Investigation of failure mechanisms and migration of organic contaminant at Wilsonville, Illinois. Spring 1989 Groundwater Monitoring Review, pp. 82-89.

Huyakorn, P.S., Springer, E.P., Guvanasen, V., Wadsworth, T.D. 1986. A three-dimensional finite element model for simulating water flow in variably saturated porous media. Water Resources Res., 22 (13), pp. 1790-1808.

King. K.S., Quigley, E.M., Fernandez, F. et al. 1993. Hydraulic conductivity and diffusion monitoring of the Keele Valley landfill liner, Maple, Ontario. Canadian Geotechnical Journal, 30.

Koerner, R.M. 1990. Preservation of the environment via geosynthetic containment systems. In Proceedings of the 4th International Conference on Geotextiles and Geomembranes, Vol. III, The Hague, pp. 975-988.

MoEE. 1994. Incorporation of the reasonable use concept into MOEE groundwater management activities. Policy 15-08, Ministry of the Environment and Energy, March, 1993.

Molson, J.W., and Frind, E.O. 1991. Regional Municipality of Durham Contingency Landfill Site Assessment: Addendum II, 3D Groundwater Flow Model, Institute for Groundwater Research, University of Waterloo, Waterloo, Ontario.

Molson, J.W., and Frind, E.O. 1993. Numerical simulation of groundwater flow and contaminant transport at the Keele Valley Landfill. Waterloo Centre for Groundwater Research.

Pandit, A., Panigrahi, B.K., Peyton, L., and Sayed, S.M. 1993. Strengths and limitations of ten widely used groundwater transport models. Proceedings of the Joint CSCE-ASCE National Conference on Environmental Engineering, Montreal, Canada, July, pp. 1249-1256.

Panigrahi, B.K., Pandit, A., Hebson, C.S. and Rowe, R.K. 1993. Input parameter requirements for groundwater models. Joint CSCE-ASCE National Conference on Environmental Engineering, Montreal, July, Vol. 2, pp. 1265-1272.

Rowe, R.K. 1991a. Contaminant impact assessment and the contaminating lifespan of landfills. Canadian Journal of Civil Engineering, 18, pp. 244-253.

Rowe, R.K. 1991b. Some considerations in the design of barrier systems. Proceedings of the 1st Canadian Conference on Environmental Geotechnics, Montreal, Canada, pp. 157-164.

Rowe, R.K., and Booker, J.R. 1985. 1-D pollutant migration in soils of finite depth. Journal of Geotechnical Engineering, ASCE, 111, pp. 479-499.

Rowe, R.K., and Booker, J.R. 1991. Pollutant migration through a liner underlain by a fractured soil. Journal of Geotechnical Engineering. ASCE, 117, pp.1902-1919.

Rowe, R.K. and Booker, J.R. 1994. A finite layer technique for modelling complex landfill history. Geotechnical Research Centre, Research Paper, GEOT- -94.

Rowe, R.K., Booker, J.R., and Fraser, M.J. 1994a. POLLUTEv6 and POLLUTE-GUI: User's Guide. GAEA Environmental Engineering Ltd., London, Ontario, Canada.

Rowe, R.K., Caers, C.J., and Chan, C. 1993. Evaluation of a compacted till liner test pad constructed over a granular subliner contingency layer. Canadian Geotechnical Journal, 30 (4), pp. 667-689.

Rowe, R.K. and Nadarajah, P. 1994. An analytical method for predicting the velocity field beneath landfills. Geotechnical Research Centre Report, GEOT-14-94, University of Western Ontario, London, Canada.

Rowe, R.K., Quigley, R.M., and Booker, J.R. 1994b. Clayey Barrier Systems for Waste Disposal Facilities. E & F N Spon (Chapman Hill), London, England.

Yanful, E.K., Nesbitt, H.W., and Quigley, R.M. 1988a. Heavy metal migration at a landfill site, Sarnia, Ontario, Canada - I: Thermodynamic assessment and chemical interpretations. Applied Geochemistry, 3, pp. 523-533.

Yanful, E.K., Quigley, R.M., and Nesbitt, H.W. 1988b. Heavy metal migration at a landfill site, Sarnia, Ontario, Canada - II: Metal partitioning and geotechnical implications. Applied Geochemistry, 3, pp. 623-629.

GLOSSARY

Advection A physical process whereby contaminants introduced into a groundwater flow system migrate in solution (as solutes) along with the movement of groundwater.

Attenuation The process whereby the concentrations of chemical species in groundwater or leachate are reduced as they move throughout the subsurface.

Background level Concentration of potential pollutants present in the environment prior to establishment, start-up and operation of a facility.

Base contour The contours of the bottom of the landfill.

Base flow The component of stream flow attributed to groundwater or spring contributions; the flow to which a stream will recede after a storm when surface runoff drops to zero.

Concentration The relative fraction of one substance in another, normally expressed in mass percent, volume percent or as mass/volume.

Contaminant Any solid or liquid resulting directly or indirectly from human activities that may cause an adverse effect on the environment.

Contaminating lifespan The period of time during which the landfill will produce contaminants at levels that could have unacceptable impact if they were discharged into the surrounding environment.

Contingency plan An organized planned and coordinated course of action to follow in case of any unexpected failure in the design of a waste management facility. A contingency plan is considered to be a backup measure only and proposed measures with a high level of probability of implementation are not contingency plans.

Cover (final) Soil (and sometimes geosynthetics) placed over the waste after completion (of a portion) of the landfill. This represents the final surface of the landfill and is intended to (a) control the infiltration of water into the landfill and(b) provide a 'pleasing' appearance while containing the waste.

Diffusion Migration of molecules or ions in air, water or a solid as a result of their own random movements from a region of higher concentration to a region of lower concentration. Diffusion can occur in the absence of any bulk air or water movement.

Dilution Increasing the proportion of solvent to solute in any solution and thereby decreasing the concentration of solute per unit volume.

Geomembrane (GM) A relatively impermeable, polymetric sheet used as a liquid and vapor barrier in geotechnical and civil engineering applications.

Groundwater recharge area An area where precipitation infiltrates downward through the soil to the water table or saturated zone.

Hydraulic conductivity The ability of soil or rock to transmit water. The higher the hydraulic conductivity, the greater the ability to transmit water. Sometimes referred to as permeability.

Hydraulic control layer (HCL) A saturated, permeable (usually coarse stone) engineered layer which may be pressurized (either naturally or by external introduction of water) to control the hydraulic gradients across a clayey barrier (liner). May be used to induce an inward hydraulic gradient across a clayey liner and hence create a hydraulic trap.

Hydraulic gradient The change in head per unit of distance in a given direction.

Hydraulic trap A term used to describe a landfill design where water flow is into the landfill and hence resists the outward movement of contaminants.

Impact The predicted effect of influence on public health and safety or the environment caused by the introduction of a proposed environmental undertaking. An impact may be positive or negative.

Landfill A land disposal site employing an engineered method of disposing wastes on land in a manner that minimizes environmental hazards by spreading wastes in thin layer, compacting the wastes to the smallest practical volume and applying cover materials at the end of each operating day.

Leachate A liquid produced from a landfill that contains dissolved, suspended and/or microbial contaminants (see contaminant) from solid waste.

Leachate collection system (LCS) An engineered system designed to collect and remove leachate from the landfill.

Liner A relatively thin structure of compacted natural clayey soil or manufactured material (e.g. geomembranes, geosythetic clay liners) which serves as a barrier to control the amount of leachate that reaches or mixes with groundwater.

Mitigation Any action with the intent to lessen or moderate potential negative effects; refers to methods that may be used to prevent, avoid or reduce the severity of risks, impacts or service and cost concerns.

Molecular diffusion See diffusion.

Monitoring program A program designed to test on-site and off-site effects of landfills. Such a program may be carried out over the operational life of a landfill and for several decades (or maybe centuries) following closure.

Recharge The entry of infiltration into the saturated groundwater zone together with the associated flow away from the water table within the saturated zone. Generally, an area where water is added to the groundwater system by virtue of the infiltration of precipitation or surface water, and subsequently moves downward to the water table, is referred to as a recharge area.