CHAPTER 4

CONCEPTUAL AND STOCHASTIC MODELING RESULTS

4.1 Horizontal Trench

Results for modeling of the horizontal trench are reported below. Data for constant and intermittent (8 hr on/16 hr off) are presented separately. A typical saturation iso-cline is shown in Figure 4.1.1. To interpret the results, the lateral (horizontal) and upward (vertical) movement of leachate from the center of the trench were determined. The lateral movement distance was calculated as the maximum distance to the 45% saturation iso-cline while the upward movement was calculated as the vertical distance from the top of the trench to the uppermost 45% saturation iso-cline (see Figure 4.1.1). The initial saturation was 40% in these simulations, however the 45% saturation iso-cline was used to calculate the extent of upward and lateral movement, based on the contouring results. The 40% iso-cline were quite jagged which made identification of the leachate movement distances difficult and subjective. The use of the 45% saturation iso-cline produced cleaner figures from which data could be more easily interpreted.

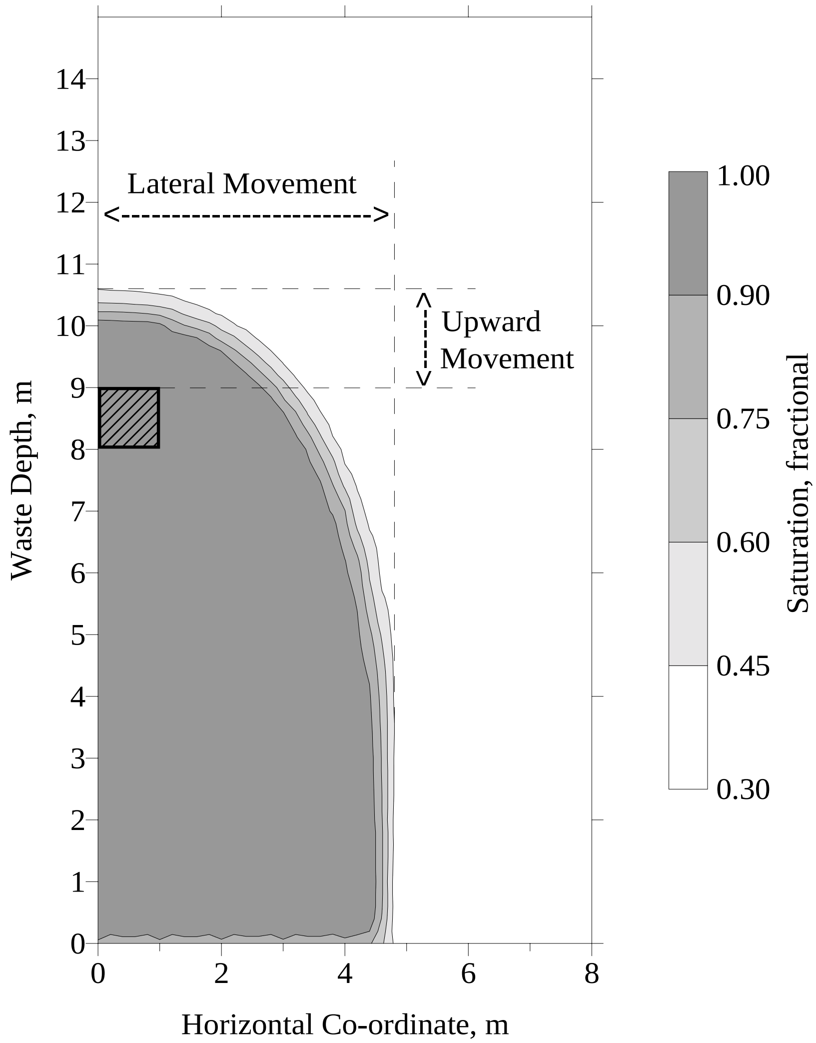


Figure 4.1.1. Schematic depicting the calculation method for the lateral and upward movement, leachate applied continuously at 8 m^3/m/day for one week, waste permeability = $1x10^{-3}$ cm/s.

4.1.1 Constant Operation Results

This section addresses continuous operation of the horizontal trench at application rates of 2, 4, and 8 m^3/m/day. Permeabilites of 10^{-3}, 10^{-4}, and 10^{-5} cm/s were modeled for each application rate. Figures 4.1.2 and 4.1.3 present the relationship between the lateral and upward movement of leachate and the waste permeability. It can be clearly seen that as the leachate application rate increases and permeability decreases both the upward and lateral movement increase.

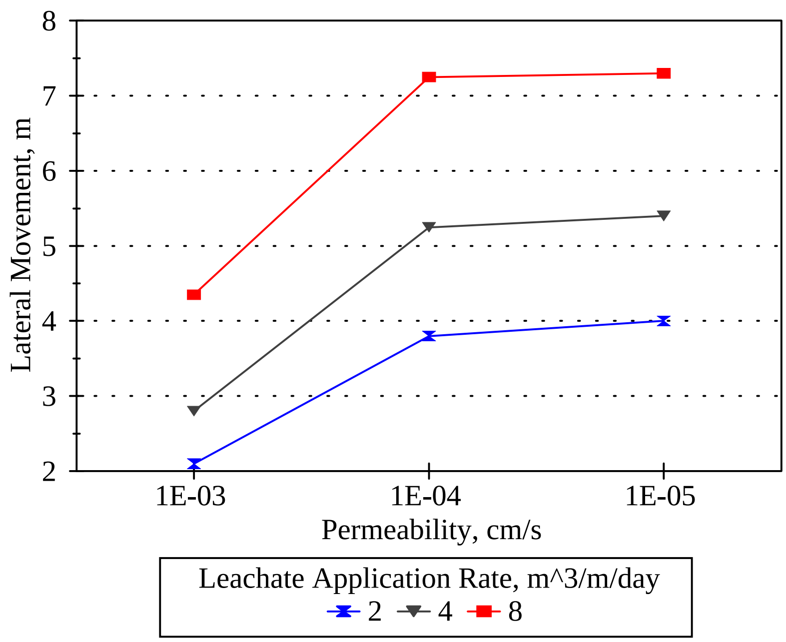


Figure 4.1.2. Maximum lateral movement versus permeability for constant leachate injection.

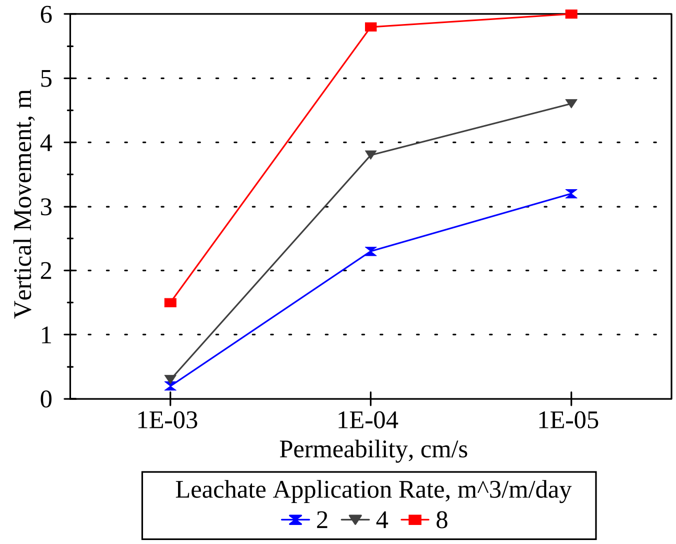


Figure 4.1.3. Maximum upward movement versus permeability for constant leachate injection.

Figures 4.1.4 and 4.1.5 plot the lateral and upward movement of leachate as a function of the leachate application rate. It can be seen in Figure 4.1.4 that there was little difference between the lateral movement results for waste with permeabilities of 10^{-4} and 10^{-5} cm/s. Figure 4.1.5 indicates that there was a difference in the upward movement for these same two permeabilities. These results suggest that as permeability decreases lateral movement may not increase significantly but that upward leachate seeps may be more likely.

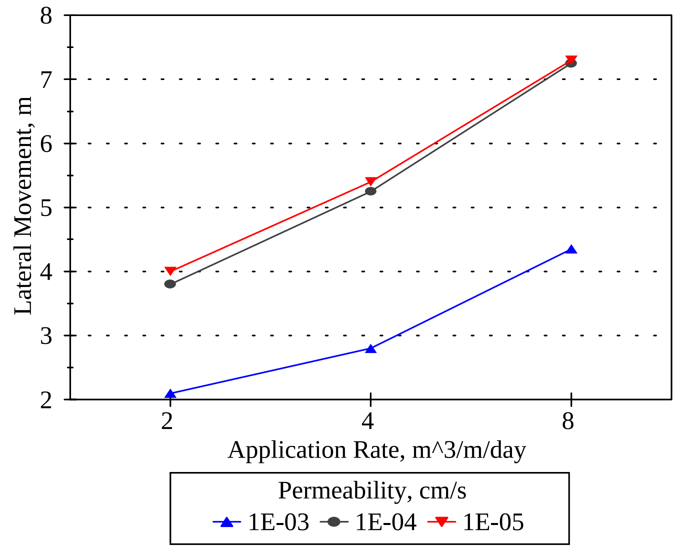


Figure 4.1.4. Lateral Movement Versus Flow Rate for Constant Leachate Injection.

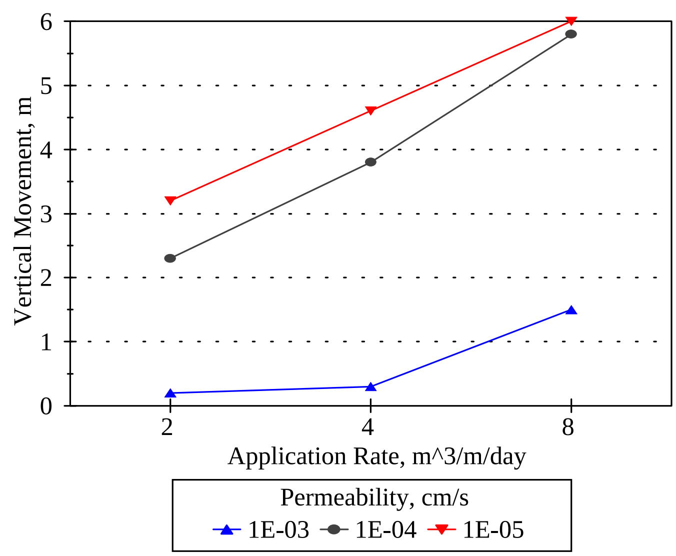


Figure 4.1.5. Upward Movement Versus Flow Rate for Constant Leachate Injection.

Figure 4.1.6 depicts the saturation iso-clines generated for constant leachate application at a rate of 4 m^3/m/day, to waste masses with permeabilities of 10^{-3}, 10^{-4}, and 10^{-5} cm/s. This figure clearly illustrates the upward and outward propagation of a saturated zone for the 10^{-4} and 10^{-5} cm/s waste masses, Figures 4.1.6b and c respectively.. There is very little difference between Figures 4.1.6b and c except for a slightly greater downward movement of leachate in Figure 4.1.6b. Saturated conditions also developed in the 10^{-3} cm/s waste mass simulation but the saturated zone did not propagate above the recirculation trench.

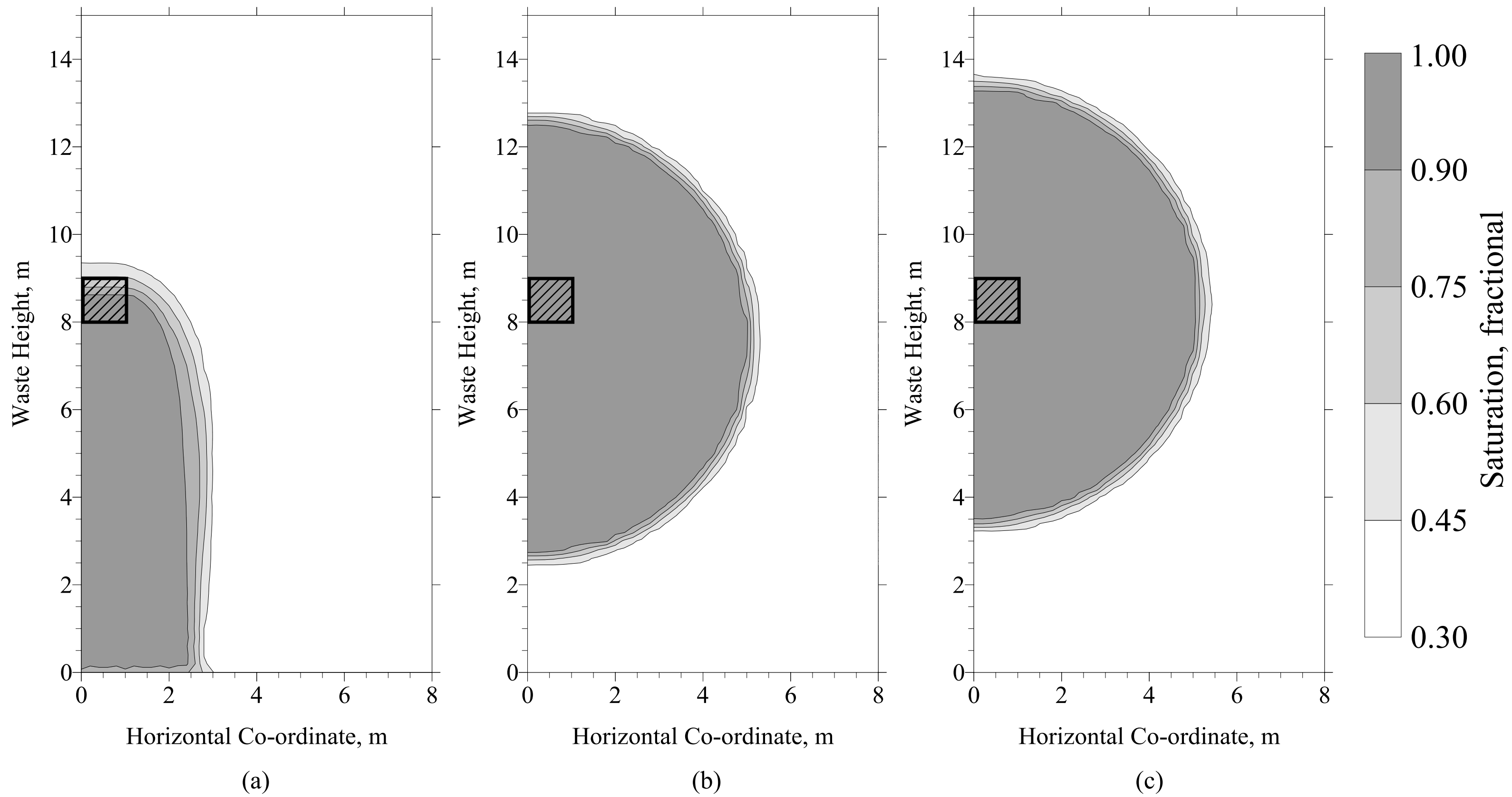


Figure 4.1.6. Saturation iso-clines for the horizontal trench operated continuously at a rate of 4 m^3/m/day for waste mass permeabilities of 10^{-3} (a), 10^{-4} (b), and 10^{-5} (c) cm/s, one week elapsed time.

4.1.2 Intermittent Operation Results

This section addresses the intermittent operation of the horizontal trench. Leachate was applied 8 hours per day for daily application rates of 2, 4, and 8 m^3/m of trench, the same daily application rates used in the continuous injection scenario. Permeabilites of 10^{-3}, 10^{-4}, and 10^{-5} cm/s were modeled for each application rate. Figures 4.1.7 and 4.1.8 present the lateral and upward movement of leachate as a function of waste permeability.

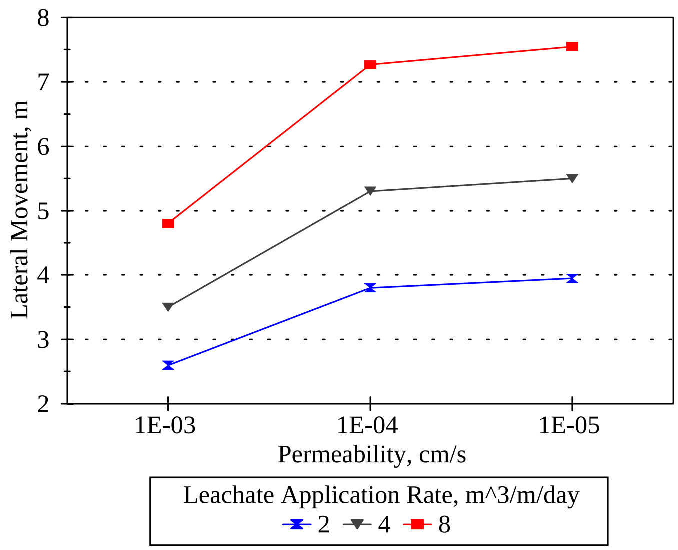


Figure 4.1.7. Maximum lateral movement versus permeability for intermittent leachate injection (8 hr on/16 hr off).

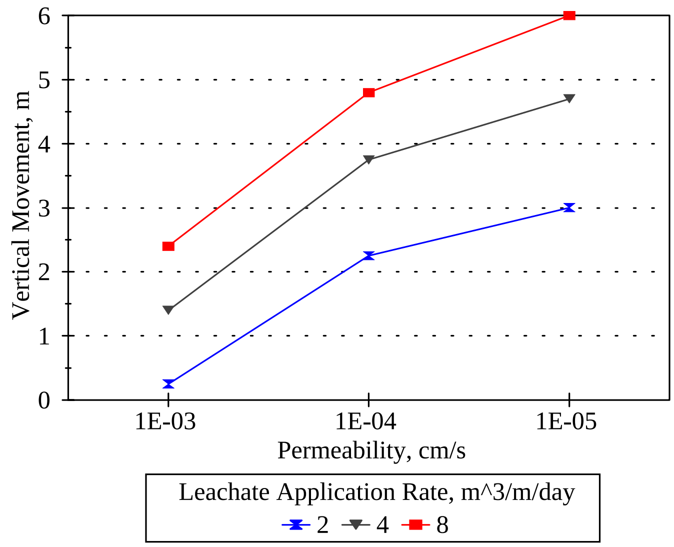


Figure 4.1.8. Maximum upward movement versus permeability for intermittent leachate injection (8 hr on/16 hr off).

As in the constant operation case, increases in the leachate application rate and decreases in permeability result in the upward and lateral movement increasing.

Figures 4.1.9 and 4.1.10 plot the maximum lateral and upward movement of leachate as a function of the leachate application rate. As was seen in the constant injection scenario, there was little difference between the lateral movement results for wastes with permeabilities of 10^{-4} and 10^{-5} cm/s but, there was a difference in the upward movement for these same two permeabilities. Again, these results suggest that as permeability decreases lateral movement may not increase significantly but that upward leachate seeps may be more likely.

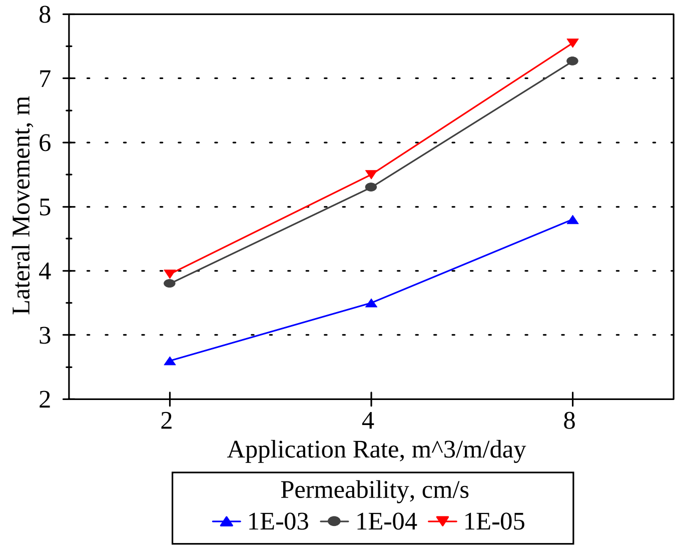


Figure 4.1.9. Lateral Movement Versus Flow Rate for Intermittent Leachate Injection (8 hr on/16 hr off).

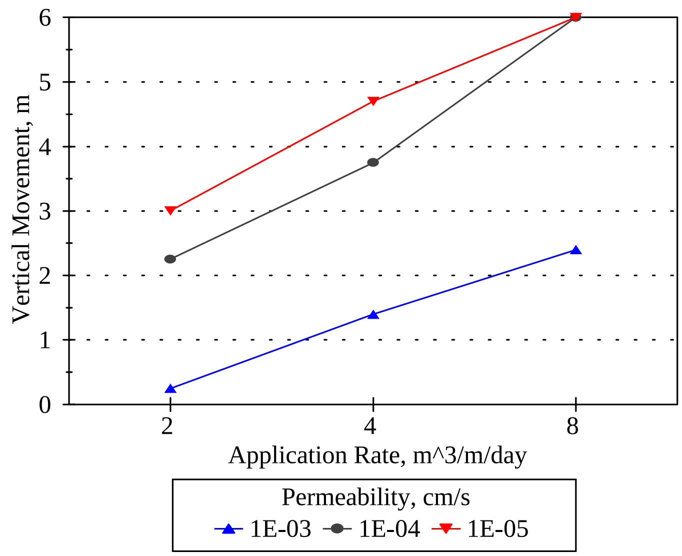


Figure 4.1.10. Upward Movement Versus Flow Rate for Intermittent Leachate Injection (8 hr on/16 hr off).

Figure 4.1.11 depicts the saturation iso-clines generated for intermittent leachate application (8 hr on/16 hr off) at an average daily rate of 4 m^3/m, to waste masses with permeabilities of 10^{-3}, 10^{-4}, and 10^{-5} cm/s. As was seen in the constant leachate application case, permeabilities of 10^{-4} and 10^{-5} cm/s produced saturated zones which propagated both upwards and outwards, Figures 4.1.11b and c respectively. As was also seen in Figures 4.1.6 b and c, there is very little difference between the results for the 10^{-4} and 10^{-5} cm/s waste masses, Figures 4.1.11b and c, except for a slightly greater downward movement of leachate for the 10^{-4} cm/s case. The 10^{-3} cm/s waste mass, Figure 4.1.11a, exhibited the most interesting results. Examination of the saturation iso-clines indicates that saturated zone drained away from the trench during the inoperative time period. The constant application scenario, Figure 4.1.6a, produced a saturated column running from the bottom of the trench to the LCS. This suggests that while intermittent operation may result in increased upward leachate movement, artesian conditions will only develop in low permeability wastes.

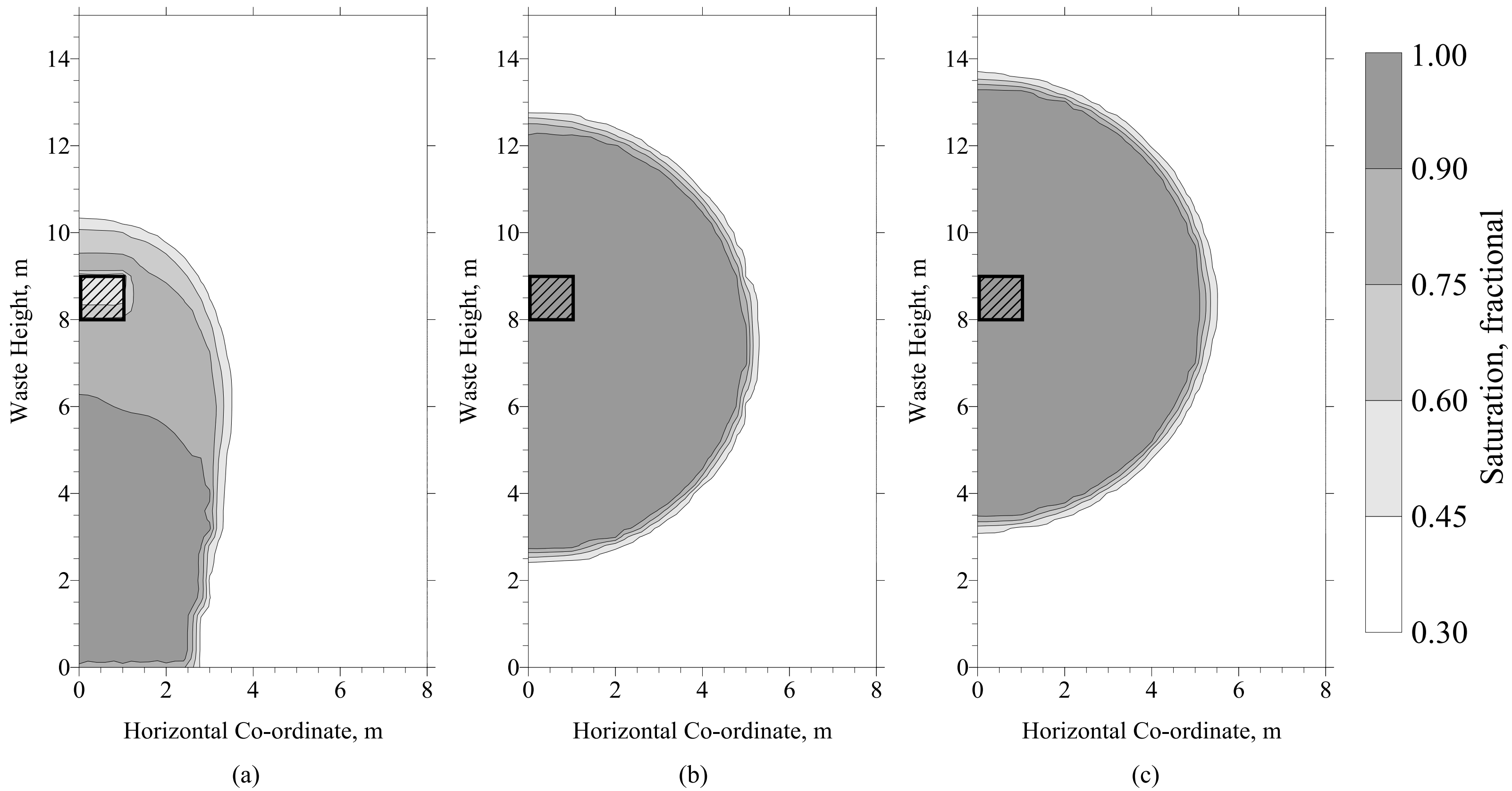


Figure 4.1.11. Saturation iso-clines for the horizontal trench operated intermittently (8 hr on /16 hr off) at an average rate of 4 m^3/m/day for waste mass permeabilities of 10^{-3} (a), 10^{-4} (b), and 10^{-5} (c) cm/s, one week elapsed time.

4.1.3 Discussion

Tables 4.1.1 presents the lateral movement results for constant and intermittent (8 hr on/16 hr off) leachate application. These data suggest that intermittent operation increases the lateral movement slightly for a high permeability waste (10^{-3} cm/s) but has no effect at lower permeabilities (10^{-4} and 10^{-5} cm/s). This behavior was most likely due to the fact that at lower permeabilities, liquid is transmitted more readily in all directions whereas at higher permeabilities, liquid movement is restricted and the greatest pressure gradient will be in the vertical direction. In practice, leachate should be recirculated with less frequency (one day per week) at higher rates which will result in increased lateral movement.

Table 4.1.1. Maximum lateral movement for constant and intermittent leachate application via the horizontal trench.

Permeability, cm/s	Constant Application			Intermittent Application (8 hr on/16 hr off).		
	Application Rate, m^3/m/day			Application Rate, m^3/m/day		
	2	4	8	2	4	8
10^{-3}	2.1	2.8	4.35	2.6	3.5	4.8
10^{-4}	3.8	5.25	7.25	3.8	5.3	7.27
10^{-5}	4	5.4	7.3	3.95	5.5	7.55

Table 4.1.2 presents the upward movement results for constant and intermittent (8 hr on/16 hr off) leachate application. Inspection of these data indicates that at a waste permeability of 10^{-3} cm/s, intermittent operation results in an increase in the upward movement of leachate as compared to constant injection. However, while there is a slight increase in upward movement, the leachate drains away when leachate is not applied and head does not build up.

Table 4.1.2. Maximum upward movement for constant and intermittent leachate application via the horizontal trench.

Permeability, cm/s	Constant Application			Intermittent Application (8 hr on/16 hr off).		
	Application Rate, m^3/m/day			Application Rate, m^3/m/day		
	2	4	8	2	4	8
10^{-3}	0.2	0.3	1.5	0.25	1.4	2.4
10^{-4}	2.3	3.8	5.8	2.25	3.75	6
10^{-5}	3.2	4.6	6	3	4.7	6

Figure 4.1.12a clearly shows that leachate is able to drain away from the trench once application has stopped while Figure 4.1.12b shows a predominantly saturated influence area indicating that leachate movement under gravity forces is slow and that

there is the potential for the development of artesian conditions as noted by Townsend et al. (1994).

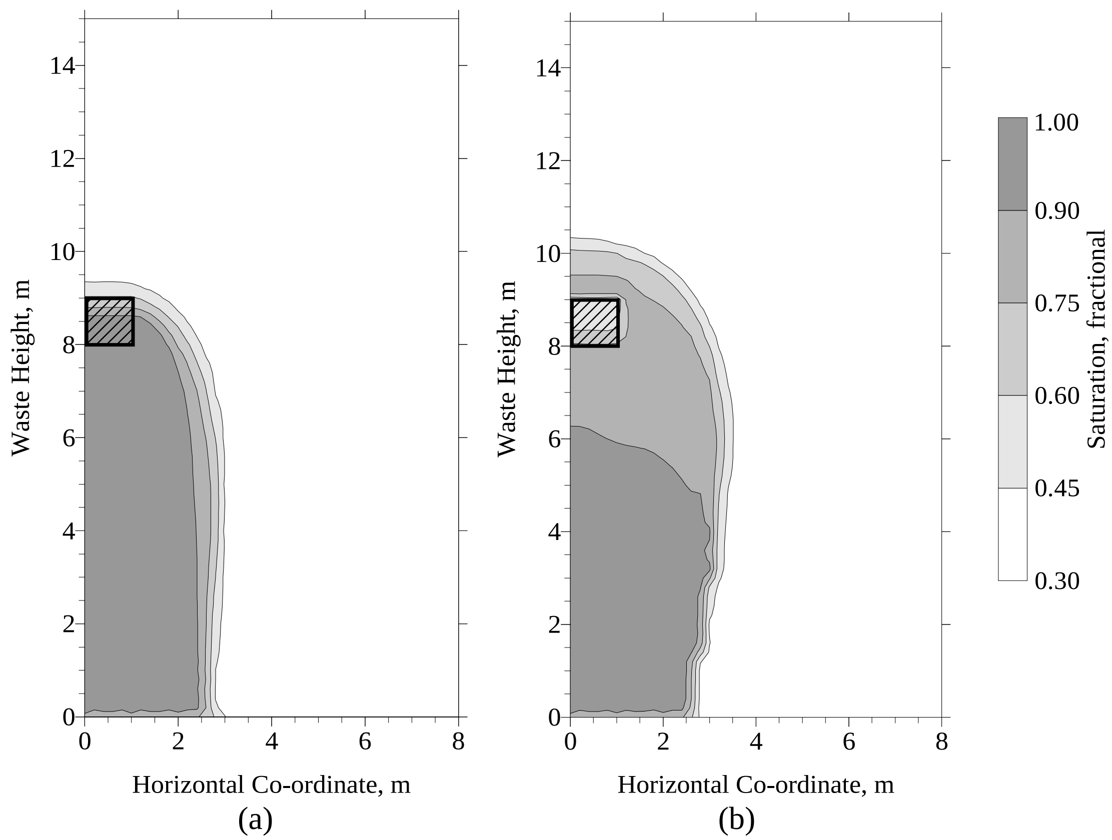


Figure 4.1.12. Saturation iso-clines for the horizontal trench operated constantly (a) and intermittently (b) at an average rate of $4m^3$/m/day after one week. Waste permeability = 10^{-3} cm/s.

Intermittent operation had little effect on the upward movement of leachate for either of the lower permeability wastes (10^{-4} and 10^{-5} cm/s). This was due to the fact that at these lower permeabilties, leachate was unable to drain away to any significant degree during the inoperative periods. In lower permeability wastes, it may be necessary to limit the rate at which leachate is applied in order to prevent surface seep problems. However, lowering the rate at which leachate is applied will also decrease the lateral area impacted.

The saturation profiles shown also suggest that the ability to pump leachate at high rates will be limited not only by pump size but, also by the proximity of the trench to the landfill surface and side slopes. Overpumping may result in leachate seeps at the sides of the landfill or upward movement of leachate and possibly artesian conditions at the landfill surface. Either of these conditions will result in operational problems and, potentially, regulatory violations. Therefore, conservative pumping of trenches near the vertical and horizontal boundaries of the landfill would be prudent.

4.2 Vertical Well

Results for modeling of the vertical well are reported below. Data for constant and intermittent (8 hr on/16 hr off) operation are shown separately. The 45% iso-cline was again used for calculating lateral movement (Figure 4.2.1). Vertical movement was not recorded as it was small, less than 1 m, in all cases.

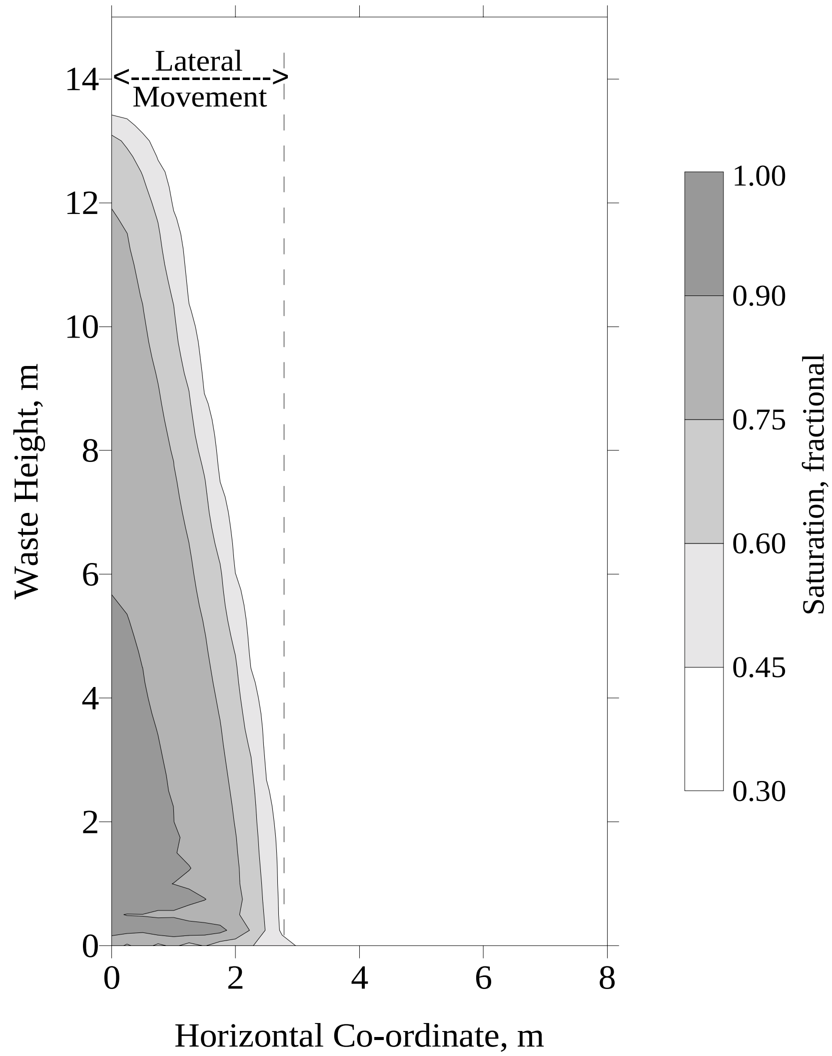


Figure 4.2.1. Calculation of lateral movement, leachate applied intermittently (8 hr on/16 hr off) at 10 m^3/m/day for three weeks, waste permeability = $1x10^{-3}$ cm/s.

4.2.1 Constant Operation

Figure 4.2.2 presents data on the effect of time and flow rate on the lateral movement of leachate from the vertical well for continuous leachate application to a waste with a permeability of 10^{-3} cm/s. Inspection of this figure shows that there is only a slight increase in leachate movement after three weeks of operation.

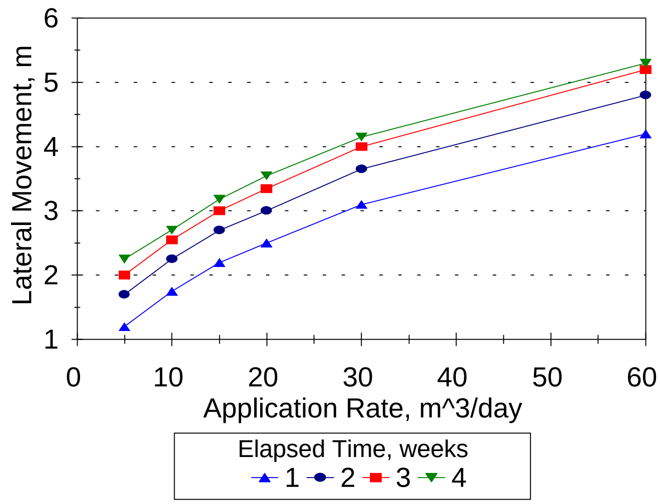


Figure 4.2.2. Lateral movement versus flow rate for one to four weeks of constant leachate application to a waste mass with a permeability of 10^{-3} cm/s.

Figures 4.2.3 through 4.2.5 plot the lateral movement of leachate versus the leachate application rate and the waste permeability for elapsed times of one, two, and three weeks. As would be expected from the trench results previously discussed, lateral movement increased with decreasing permeability and increasing application rates.

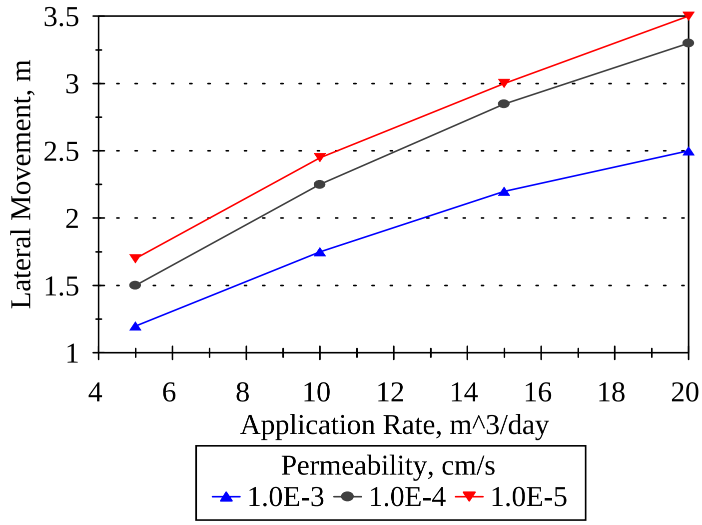


Figure 4.2.3. Lateral movement versus flow rate after one week of constant leachate application.

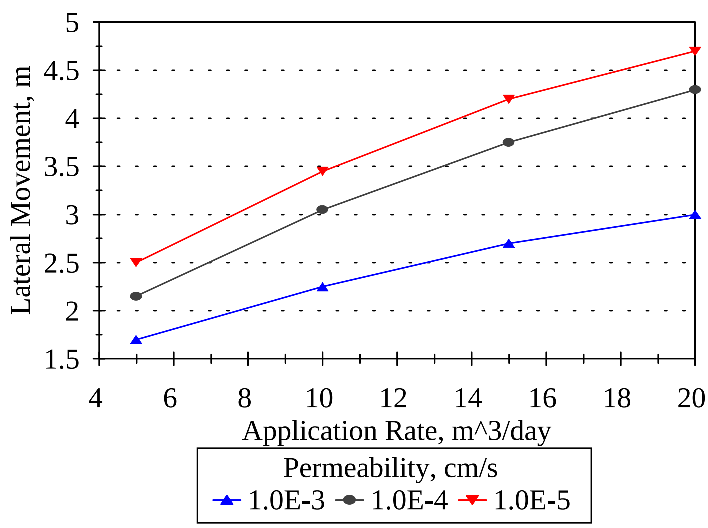


Figure 4.2.4. Lateral movement versus flow rate after two weeks of constant leachate application.

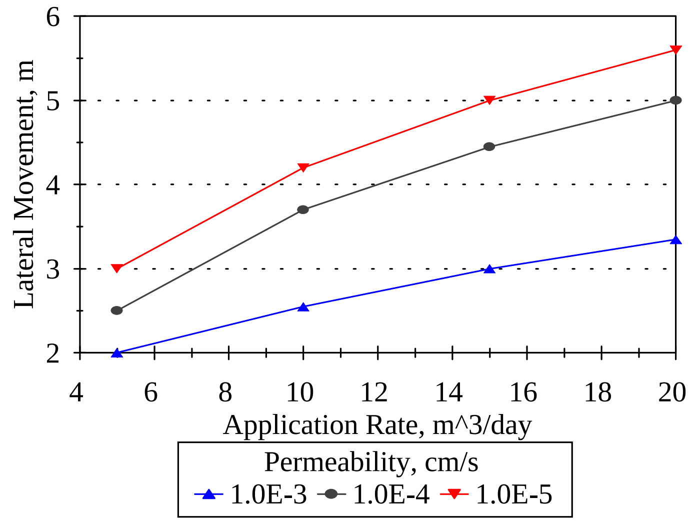


Figure 4.2.5. Lateral movement versus flow rate after three weeks of constant leachate application.

Figure 4.2.6 depicts the saturation iso-clines generated for constant leachate application at a rate of 10 m^3/day, to waste masses with permeabilities of 10^{-3}, 10^{-4}, and 10^{-5} cm/s. This figure clearly illustrates the propagation of the saturated zone and indicates that as permeability decreases, lateral movement increases. Inspection of the saturation iso-clines generated for each permeability scenario indicate that the area impacted in the 10^{-4} and 10^{-5} cm/s was predominantly saturated. The saturation iso-clines for a waste permeability of 10^{-3} cm/s indicate that the area impacted has a range of saturations propagating outwards from a saturated zone near the well surface.

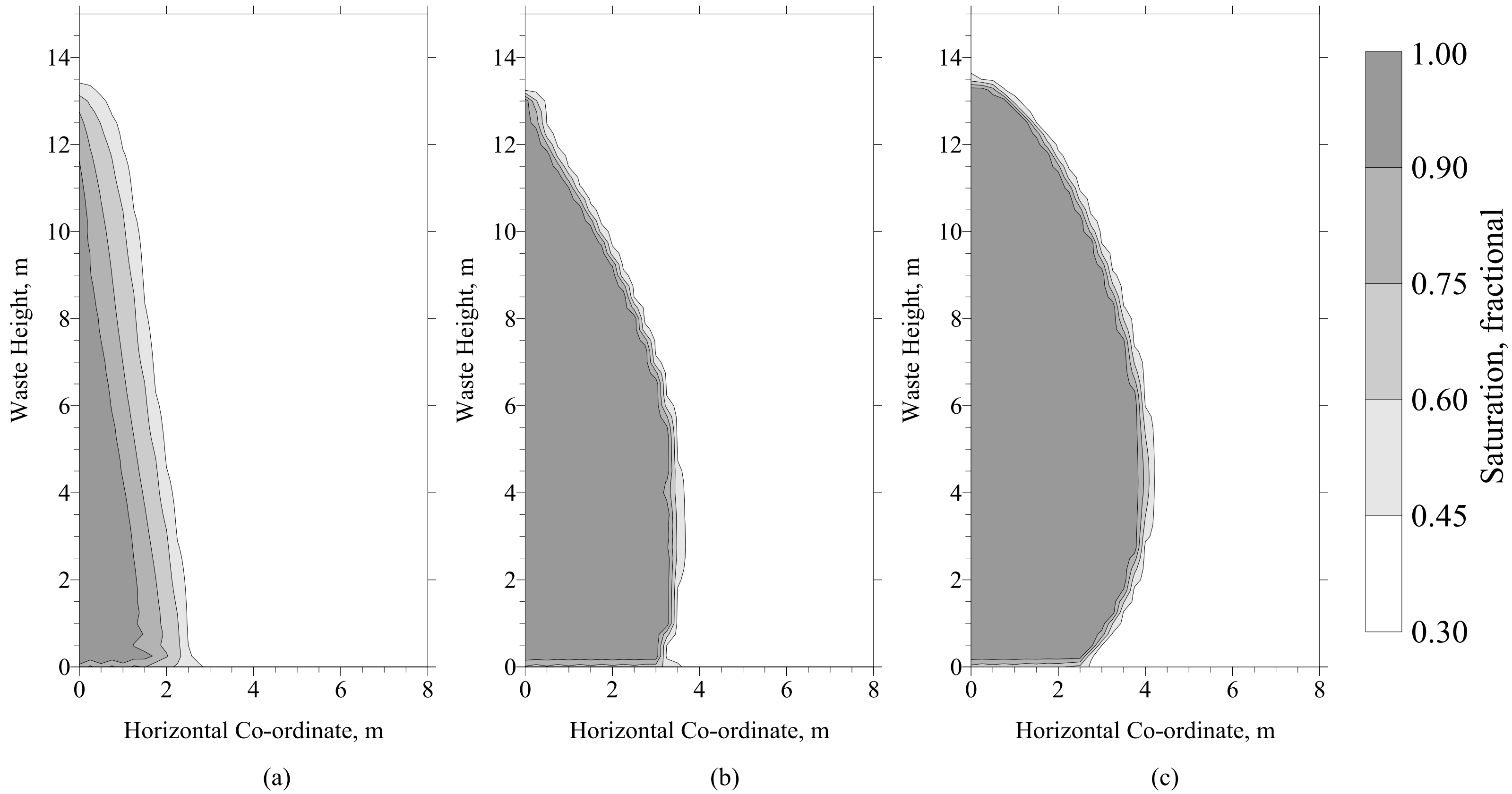


Figure 4.2.6. Saturation iso-clines for the vertical well operated continuously at a rate of 10 m^3/day for waste mass permeabilities of 10^{-3} (a), 10^{-4} (b), and 10^{-5} (c) cm/s, three weeks elapsed time.

4.2.2 Intermittent Operation

Figure 4.2.7 illustrates the effect of time and flow rate on the lateral movement of leachate from the vertical well for intermittent leachate application (8 hr on/16 hr off) to a waste with a permeability of 10^{-3} cm/s.

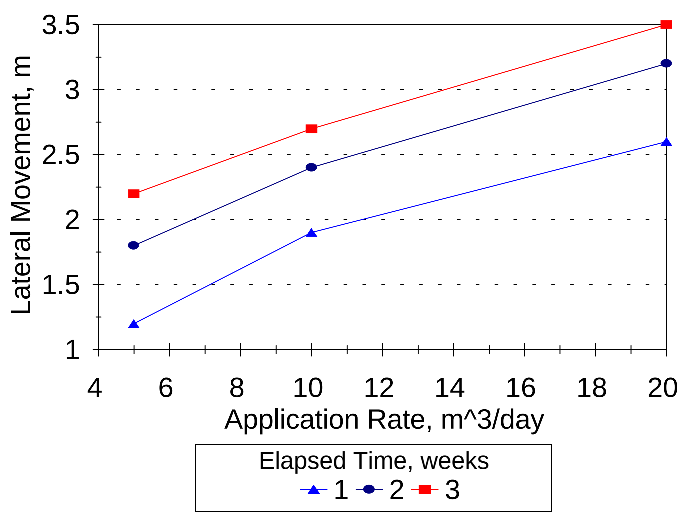


Figure 4.2.7. Lateral movement versus flow rate for one to three weeks of intermittent leachate application (8 hr on/16 hr off) to a waste mass with a permeability of 10^{-3} cm/s.

Figures 4.2.8 through 4.2.10 present the lateral movement of leachate as a function of the leachate application rate for elapsed times of one, two, and three weeks. As would be expected from the trench results previously discussed, lateral movement increased with decreasing permeability and increasing application rates.

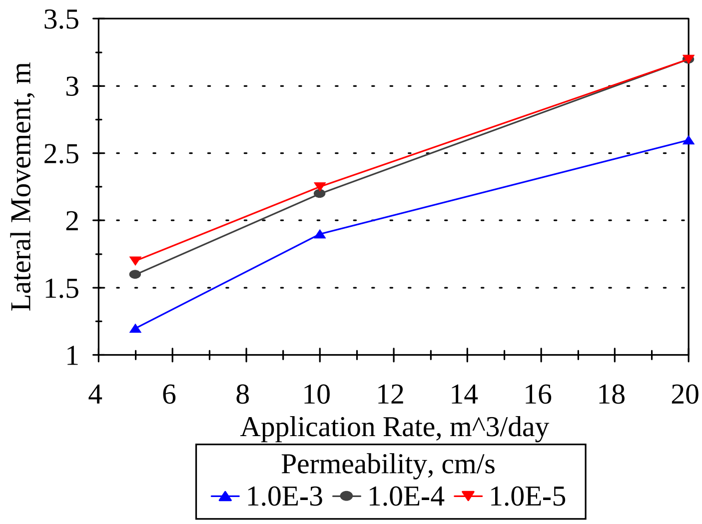


Figure 4.2.8. Lateral movement versus flow rate after one week of intermittent leachate application (8 hr on/16 hr off).

Figure 4.2.11 depicts the saturation iso-clines generated for intermittent leachate application (8 hr on/16 hr off) at an average daily rate of 10 m^3, to waste masses with permeabilities of 10^{-3}, 10^{-4}, and 10^{-5} cm/s. As was seen in the constant application scenario, lateral movement increases as permeability decreases. Waste permeabilities of 10^{-4} and 10^{-5} cm/s again produced a predominantly saturated impact area while the 10^{-3} cm/s waste mass resulted in a range of saturations propagating outwards from a saturated

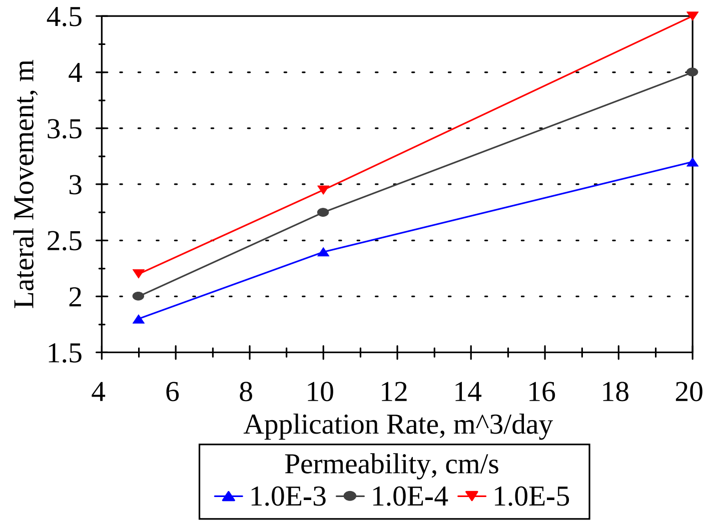


Figure 4.2.9. Lateral movement versus flow rate after two weeks of intermittent leachate application (8 hr on/16 hr off).

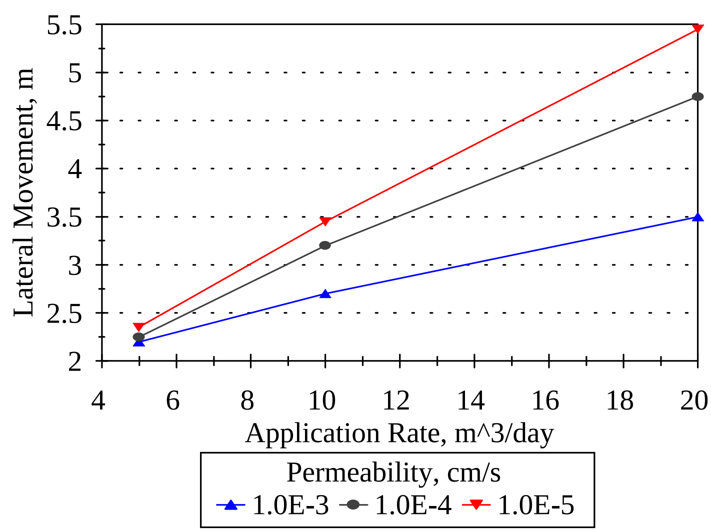


Figure 4.2.10. Lateral movement versus flow rate after three weeks intermittent leachate application (8 hr on/16 hr off).

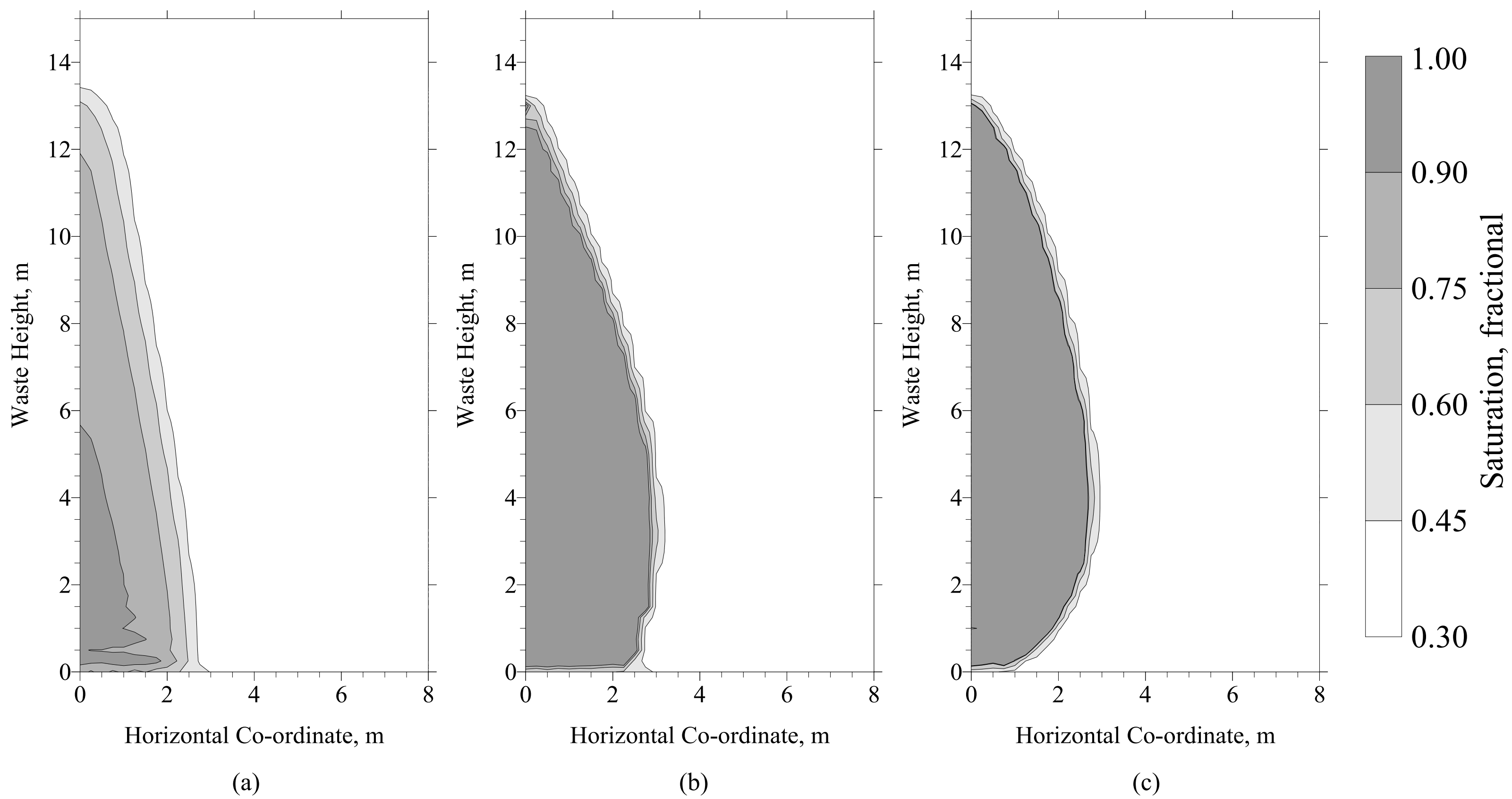


Figure 4.2.11. Saturation iso-clines for the vertical well operated intermittently (8 hr on /16 hr off) at an average rate of 10 m^3/day for waste mass permeabilities of 10^{-3} (a), 10^{-4} (b), and 10^{-5} (c) cm/s, three weeks elapsed time.

zone near the well surface. Inspection of Figure 4.2.1a also indicates that intermittent operation enables the saturated zone to drain away during the periods between leachate application.

4.2.3. Discussion

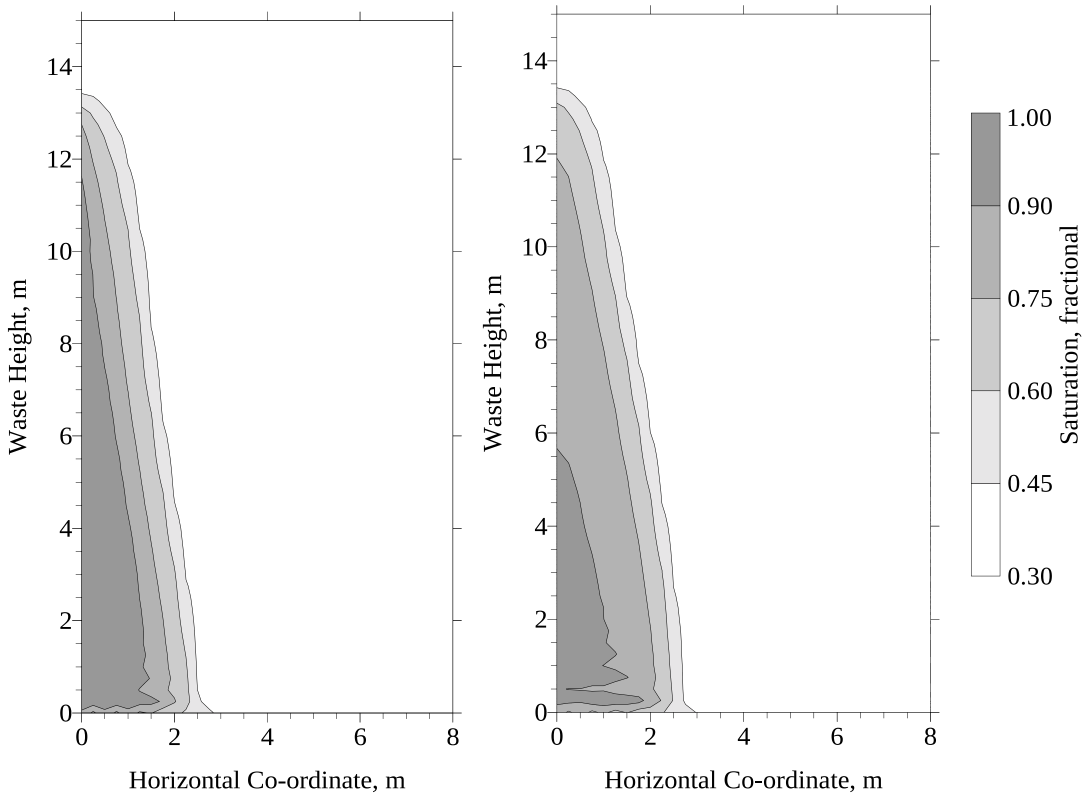
Table 4.2.1 presents the results for constant and intermittent leachate application after three weeks of operation. The lowest lateral movement was for leachate applied constantly to a waste mass with a permeability of 10^{-3} cm/s while the highest lateral movement was for leachate applied constantly to a waste mass with a permeability of 10^{-5} cm/s.

These data also indicate that for the high permeability waste mass (10^{-3} cm/s), intermittent operation increases lateral spreading while for the lower permeability waste masses (10^{-4} and 10^{-5} cm/s), intermittent operation resulted in a reduction in the lateral spreading. This behavior can be attributed to the ability of leachate to move laterally and vertically and the proximity of the vertical well to the drainage layers. Figure 4.2.12 depicts the saturation iso-clines for leachate applied at an average rate of 10 m^3/day to a waste mass with a permeability of 10^{-3} cm/s. Inspection of this figure indicates that the saturated zone drains significantly between leachate applications for the intermittent application scenario. Intermittent application results in higher-short term application rates which drive leachate laterally into the waste mass.

Table 4.2.1. Maximum lateral movement for constant and intermittent leachate application via the horizontal trench.

Permeability, cm/s	Constant Application			Intermittent Application (8 hr on/16 hr off).		
	Application Rate, m^3/m			Application Rate, m^3/m		
	5	10	20	5	10	20
10^{-3}	2	2.55	3.35	2.2	2.7	3.5
10^{-4}	2.5	3.7	5	2.25	3.2	4.75
10^{-5}	3	4.2	5.6	2.35	3.45	5.45

Figure 4.2.13 depicts the saturation iso-clines for leachate applied at an average rate of 10 m^3/day to a waste mass with a permeability of 10^{-5} cm/s. In this case, the low permeability of the waste inhibits leachate movement. Intermittent operation then results in the build up of pressure which is dissipated more quickly by movement in the vertical direction (there would be a higher pressure gradient in the vertical direction than the horizontal direction). Constant operation builds up head continuously, forcing leachate to move both vertically and horizontally into the waste mass.



(a) (b)

Figure 4.2.12. Saturation iso-clines for the vertical well operated constantly (a) and intermittently (b) at an average rate of 10 m^3/day for three weeks. Waste permeability = 10^{-3} cm/s.

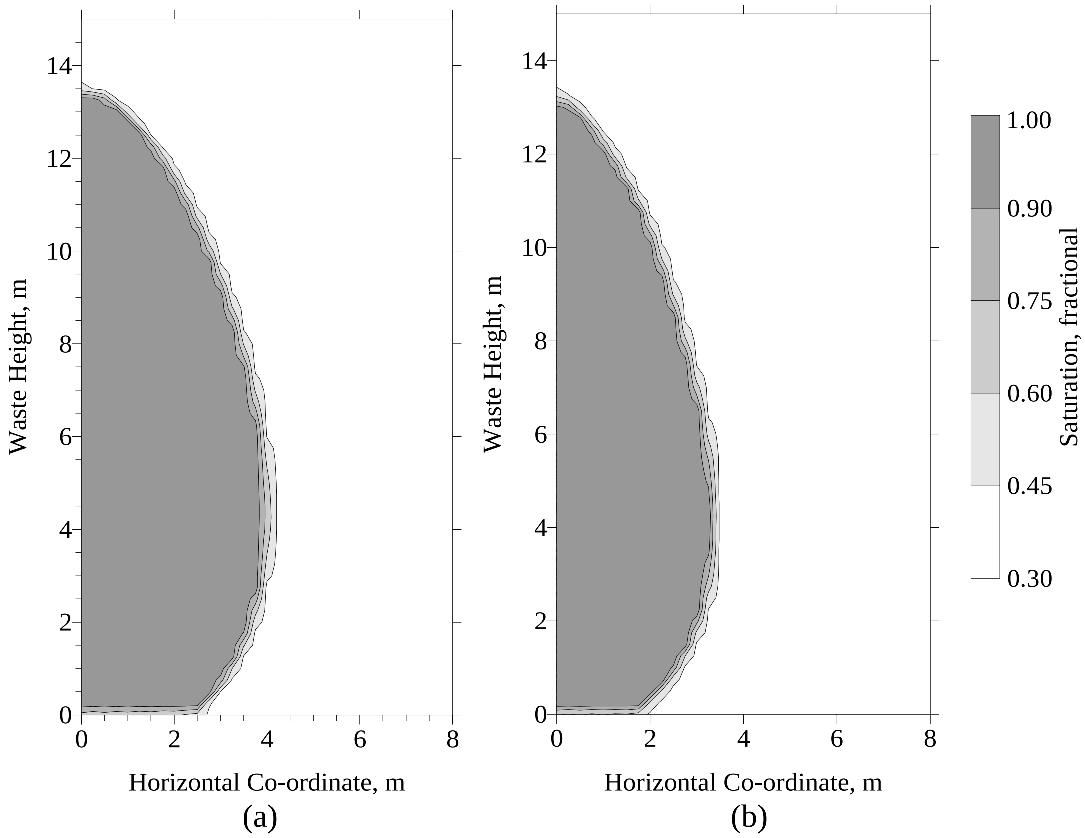


Figure 4.2.13. Saturation iso-clines for the vertical well operated constantly (a) and intermittently (b) at an average rate of 10 m^3/day for three weeks. Waste permeability = 10^{-5} cm/s.

4.3 Daily Cover Material Effects

The permeability of daily and intermediate cover materials is as varied as the materials used, cover materials typically employed include clay, sand, shredded tires, used carpet, foams, and removable geo-textiles or tarps. The location and thickness of these layers can seriously impact leachate flow.

The selection and application of daily and intermediate covers is of particular importance to successful leachate recirculation. The use of low permeability materials will significantly impede vertical movement of leachate resulting in perched lenses of leachate and potentially side seep problems as leachate moves laterally along the daily cover material. A leachate recirculating Delaware landfill (Miller et al., 1991) noted several perched lenses of leachate directly above daily cover materials. The waste beneath these perched lenses was found to be dry and well preserved. Once the cover material was pierced, the leachate drained quickly. Some landfill operators breach the daily cover material prior to applying the next layer of waste in order to limit perching and lateral leachate flows. The use of high-permeability materials will not inhibit vertical flow but rather, may result in lateral flow to side slopes again resulting in potential seep problems.

Figures 4.3.1 through 4.3.5 illustrate the effect of cover material permeability, breaches in the cover, and leachate application rate on leachate routing. The waste modeled in these simulations had uniform permeabilities of 10^{-3} or 10^{-4} cm/s while the cover material had permeabilities ranging from 10^{-2} to 10^{-5} cm/s, and a thickness of 0.4 m. A 1-m breach was created in two locations at each cover material level. Leachate was applied intermittently (8 hr. on/16 hr. off) for daily average rates of 2, 4, and 8 m^3/m of trench/day. The results for a waste mass with a permeability of 10^{-3} cm/s (Figures 4.3.1 through 4.3.3) best illustrate cover material effects. The movement of leachate in the 10^{-4} cm/s waste permeability simulations (Figures 4.3.4 and 4.3.5) was influenced by the imposition of a no flow upper boundary condition.

Figures 4.3.1 and 4.3.2 depict the movement of leachate through a waste mass in which the daily cover material has a lower permeability than the waste. A saturated lens of leachate can be seen perched above and moving laterally along the cover material in both figures. Leachate channels vertically through the two breaches and begins to flow downward again. The location of breaches in the cover material has an obvious effect on leachate routing. Strategic location of the breaches may then be used to control and to some degree direct leachate movement. A comparison of Figures 4.3.1 and 4.3.2 indicates that the permeability of the cover material is also important. Lateral flow was more significant and the impact of flow through breaches more pronounced for the lower permeability material (Figure 4.3.1). These figures do indicate that flow through low permeability cover materials is possible however, these materials significantly slowed the rate of vertical movement and flow through the breaches was a major leachate flow route.

Figure 4.3.3 depicts the movement of leachate through a waste mass in which the daily cover material has a higher permeability than the waste. The cover material has a slight affect on both lateral and vertical leachate movement. Close inspection of saturation iso-clines around the daily cover material indicates minimal lateral movement through the cover material but a general de-saturation around the cover layer which would imply an increase in the rate of vertical movement.

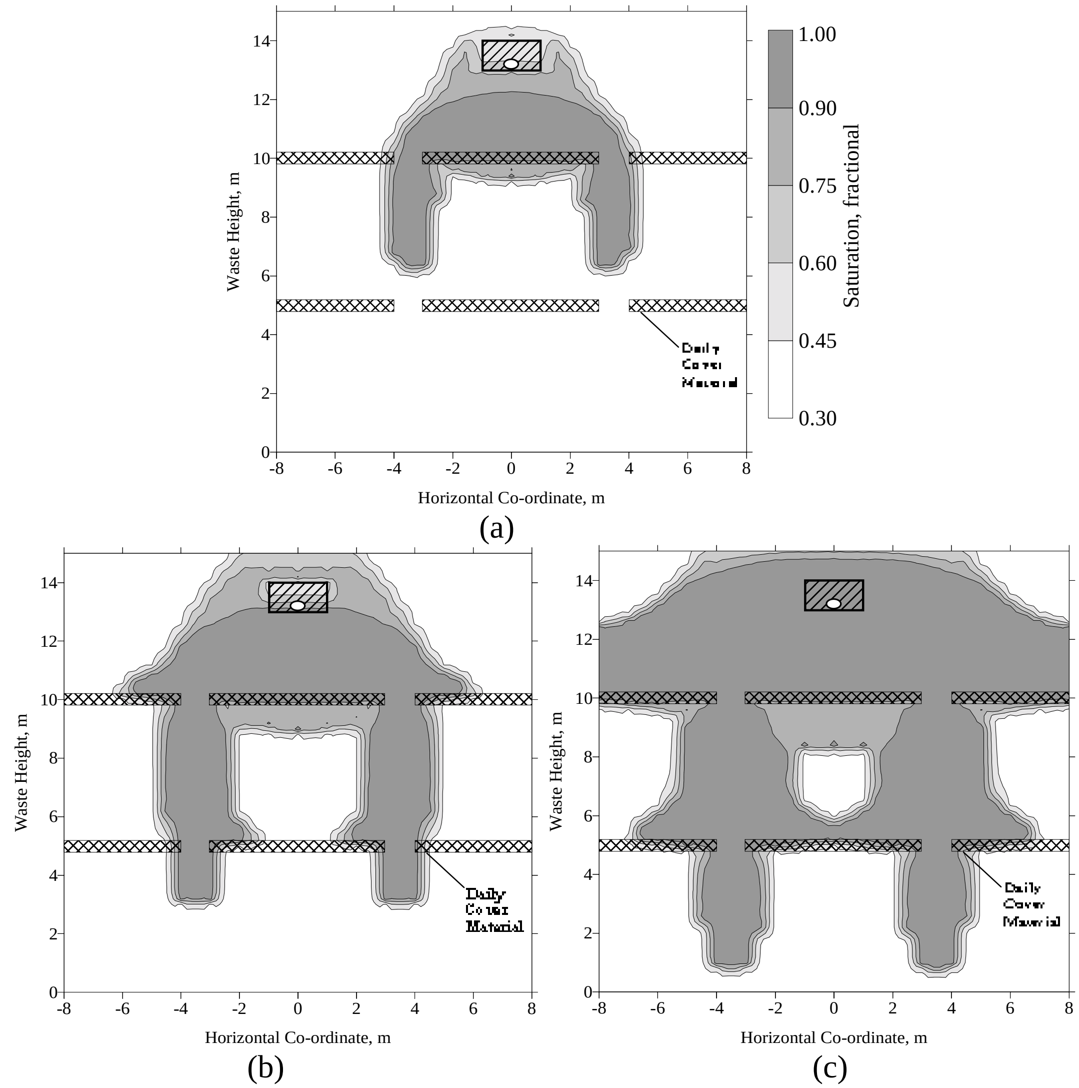


Figure 4.3.1. Comparison of leachate routing in a landfill with a low permeability daily cover material (permeability = 10^{-5} cm/s) with intermittent leachate application at a daily rate of 2, 4, and 8 m^3/m/day (a, b, and c respectively). Waste permeability = 10^{-3} cm/s.

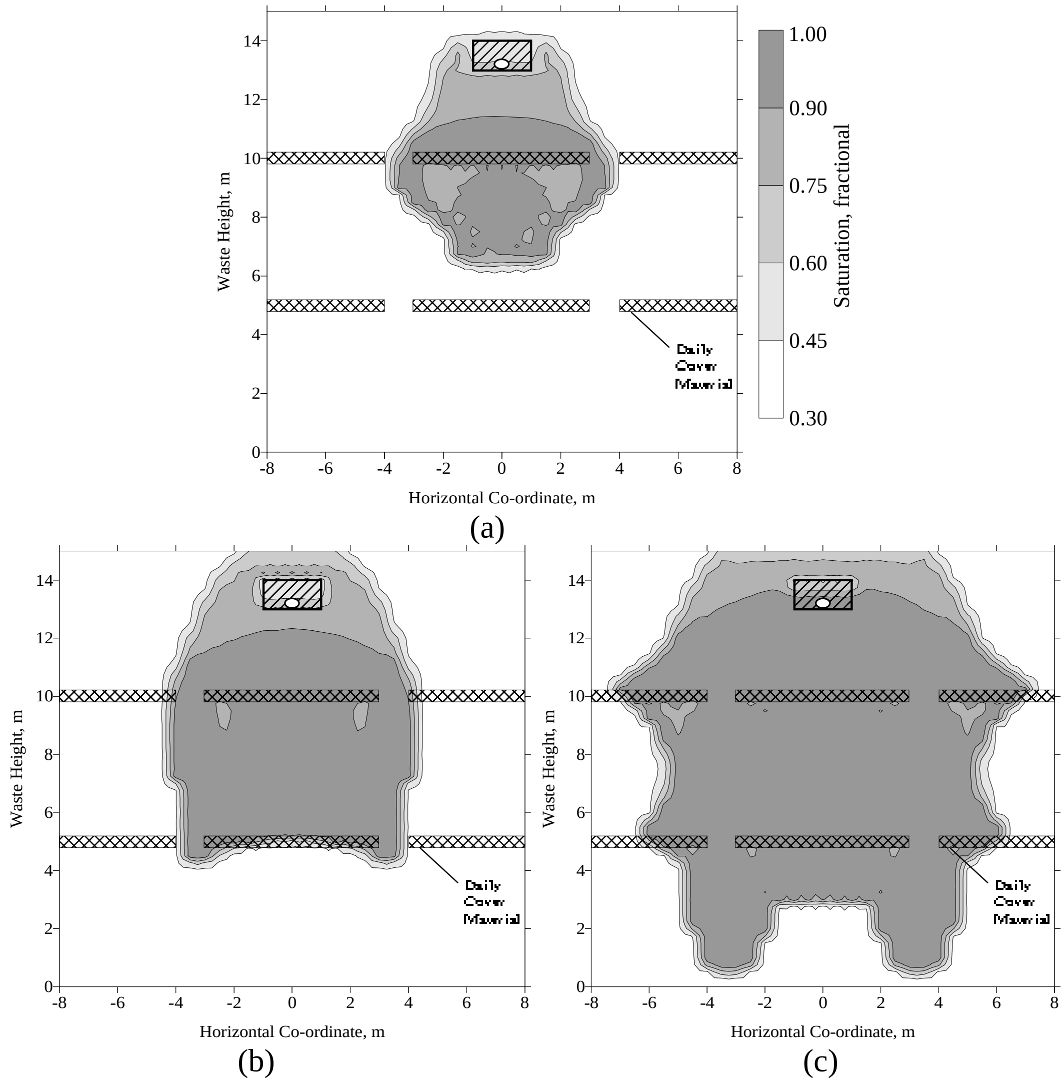


Figure 4.3.2. Comparison of leachate routing in a landfill with a low permeability daily cover material (permeability = 10^{-4} cm/s) with intermittent leachate application at a daily rate of 2, 4, and 8 m^3/m/day (a, b, and c respectively). Waste permeability = 10^{-3} cm/s.

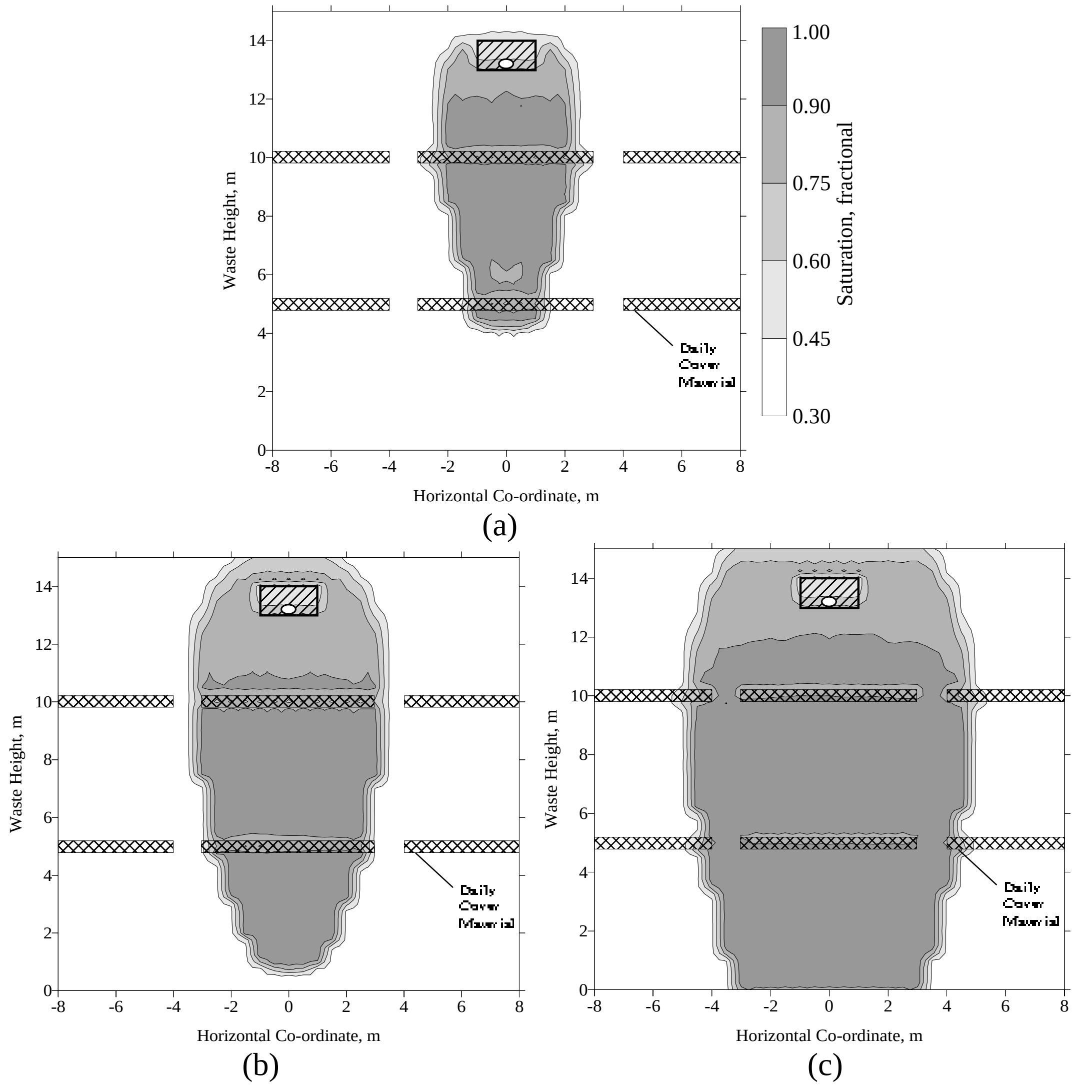


Figure 4.3.3. Comparison of leachate routing in a landfill with a high permeability daily cover material (permeability = 10^{-2} cm/s) with intermittent leachate application at a daily rate of 2, 4, and 8 m^3/m/day (a, b, and c respectively). Waste permeability = 10^{-3} cm/s.

The movement of leachate through a lower permeability waste (10^{-4} cm/s) with lower (10^{-5} cm/s) and higher (10^{-3} cm/s) permeability daily covers is depicted in Figures 4.3.4 and 4.3.5, respectively. The profiles shown in Figures 4.3.4 and 4.3.5 are significantly impacted by the upper boundary condition, no-flow constraint which results in the reflection of upward moving leachate back down into the waste mass.

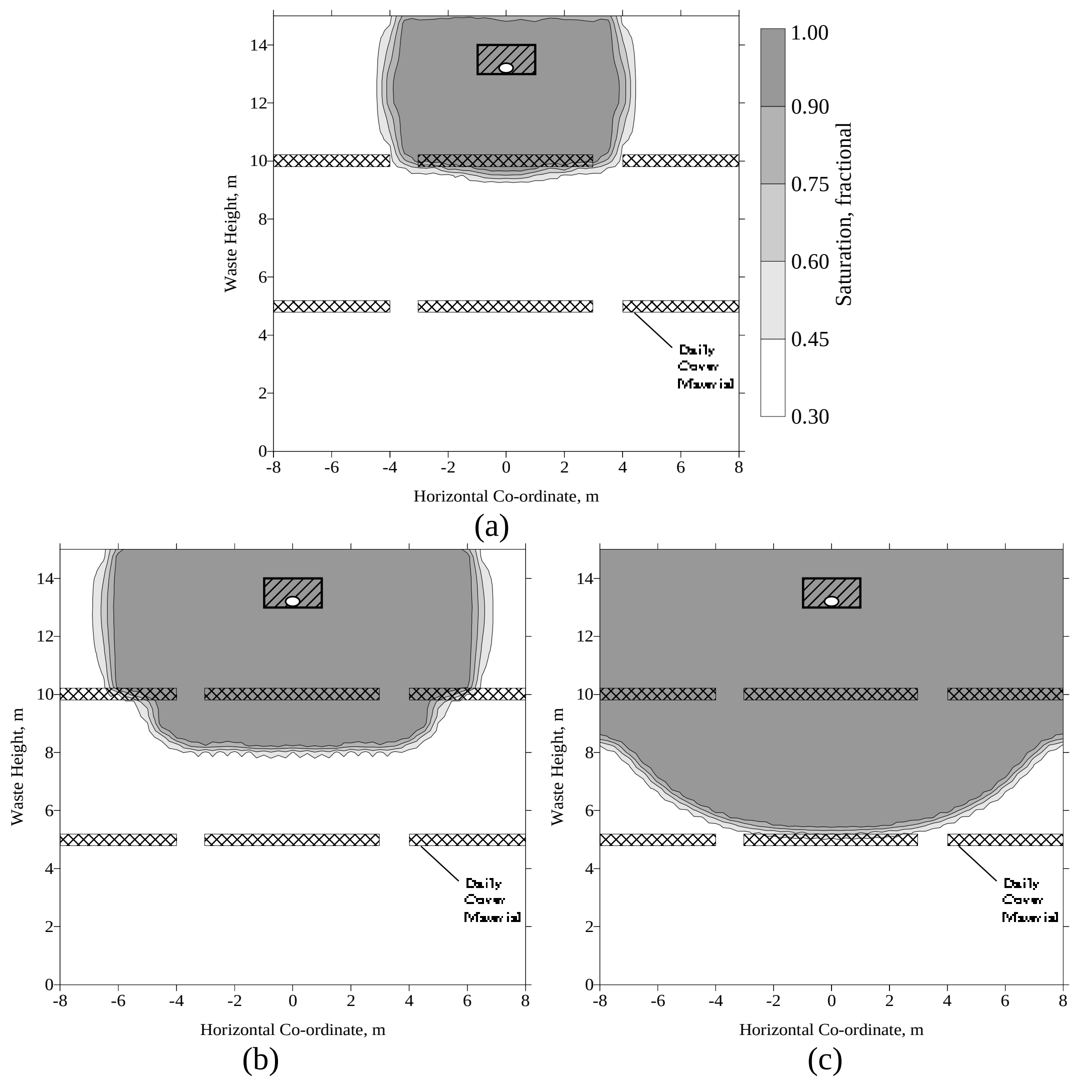


Figure 4.3.4. Comparison of leachate routing in a landfill with a low permeability daily cover material (permeability = 10^{-5} cm/s) with intermittent leachate application at a daily rate of 2, 4, and 8 m^3/m/day (a, b, and c respectively). Waste permeability = 10^{-4} cm/s.

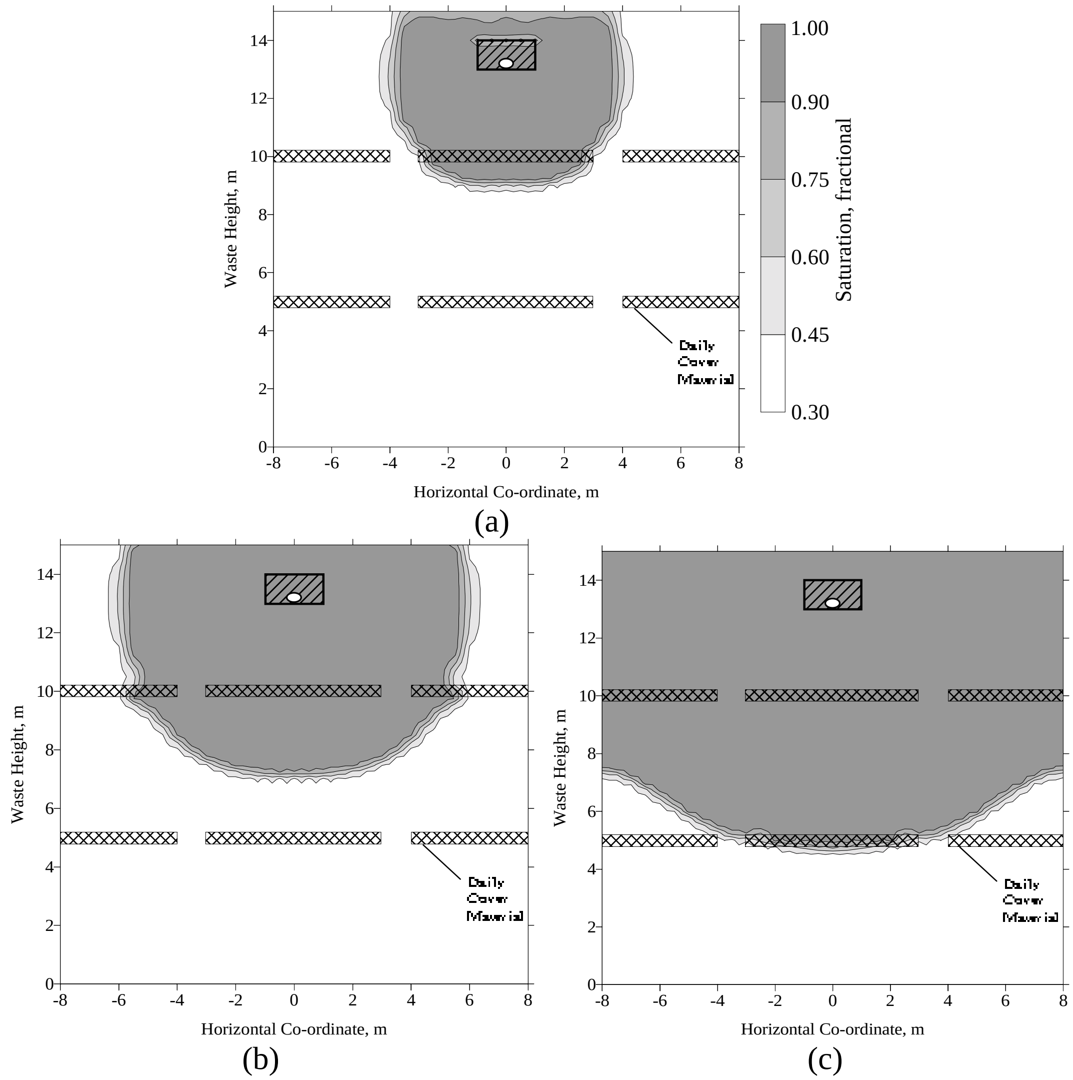


Figure 4.3.5. Comparison of leachate routing in a landfill with a high permeability daily cover material (permeability = 10^{-3} cm/s) with intermittent leachate application at a daily rate of 2, 4, and 8 m^3/m/day (a, b, and c respectively). Waste permeability = 10^{-4} cm/s.

The best situation would be to use removable or degradable cover materials within the landfill and to use low-permeability materials on the side slopes of the landfill. This cover application technique would mitigate any vertical flow problems within the fill and help to prevent side seeps. An added benefit would be increased air-space for waste placement within the landfill. Landfills which must use some type of non-degradable cover material, whether it be local soil, compost, or shredded tires, should breach horizontal layers to ensure that leachate will flow down through the fill and not along or through the cover layer.

4.4 Anisotropic Waste Conditions

While it is possible, but difficult, to predict the exact permeability of a waste mass, the nature of anisotropies within the waste mass has yet to be studied. Therefore, for the purpose of this research, it was assumed that the maximum and minimum permeabilities were oriented in the transverse and longitudinal directions. The longitudinal permeability was modeled as either 10^{-3} cm/s or 10^{-4} cm/s while the transverse permeabilities were varied one order of magnitude, above and below, the longitudinal permeability. Leachate was applied intermittently, 8 hr on/16 hr off, for a daily application rate of 4 m^3/m of trench.

Figure 4.4.1 depicts leachate routing in a waste mass with a longitudinal permeability of 10^{-3} cm/s and a transverse permeability of either 10^{-2} cm/s (Figure 4.4.1a) or 10^{-4} cm/s (Figure 4.4.1b). It can be seen clearly that the transverse movement has changed significantly from the isotropic case which produced an influence distance of 3.5 m (see Figure 4.1.6).

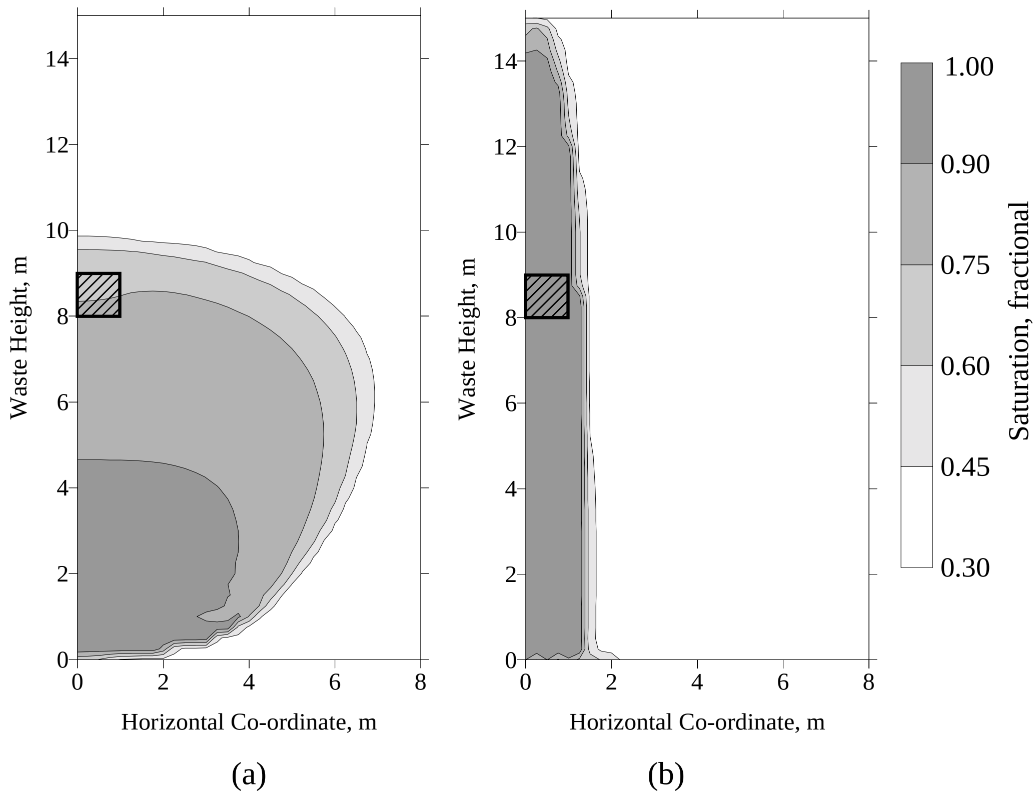
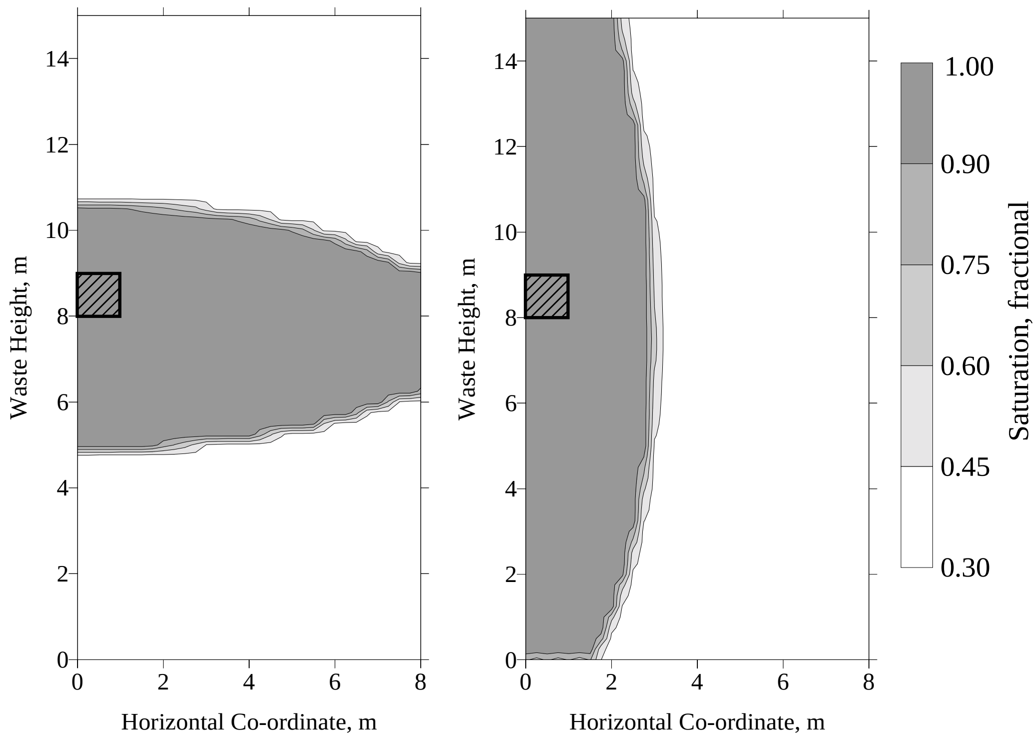


Figure 4.4.1. Leachate routing for an anisotropic waste mass with a longitudinal permeability of 10^{-3} cm/s and a transverse permeability of 10^{-2} cm/s (a) or 10^{-4} cm/s (b) after one week of operation. Leachate applied 8 hr per day at a rate of 4 m^3/m of trench/day.

Figure 4.4.2 depicts leachate routing in a waste mass with a longitudinal permeability of 10^{-4} cm/s and a transverse permeability of 10^{-3} cm/s (Figure 4.4.2a) and 10^{-5} cm/s (Figure 4.4.2b). Again, the transverse movement has changed significantly from the isotropic case which indicated an influence distance of 5.3 m (see Figure 4.1.6).



(a) (b)

Figure 4.4.2. Leachate routing for an anisotropic waste mass with a longitudinal permeability of 10^{-4} cm/s and a transverse permeability of 10^{-3} cm/s (a) or 10^{-5} cm/s (b) after one week of operation. Leachate applied 8 hr per day at a rate of 4 m^3/m of trench/day.

The simulation which generated Figure 4.4.2a was limited by the model scale resulting in the moisture profile reaching the lateral boundaries. Figure 4.4.3 was included to provide a better inspection of the effects of anisotropy and covers three weeks of trench operation. The simulation which produced Figure 4.4.3 differs from the simulation for Figure 4.4.2a in that the average leachate injection rate was decreased to 2 m^3/m/day. Despite decreasing the injection rate by half, the simulation still exceeded the boundaries somewhere between the end of the second and third weeks.

While none of these simulations provide definitive, quantitative information regarding the effects of anisotropies within the waste mass, they do indicate that anisotropic conditions will significantly impact leachate routing. Waste is generally place in thin layers which are then compacted prior to placement of the next layer of waste. This operational procedure no doubt causes a layering effect magnifying anisotropic conditions and ultimately increasing lateral leachate flows. This impact may be desirable when considering the area impacted by recirculation trenches but, it may also result in side seeps and leachate breakouts if trenches are placed too close to the landfill slopes. The evaluation of anisotropies in the landfill should be considered an important research area. An assessment of how waste placement and compaction operations affect anisotropies may enable landfill operators to develop procedures to make leachate recirculation more efficient.

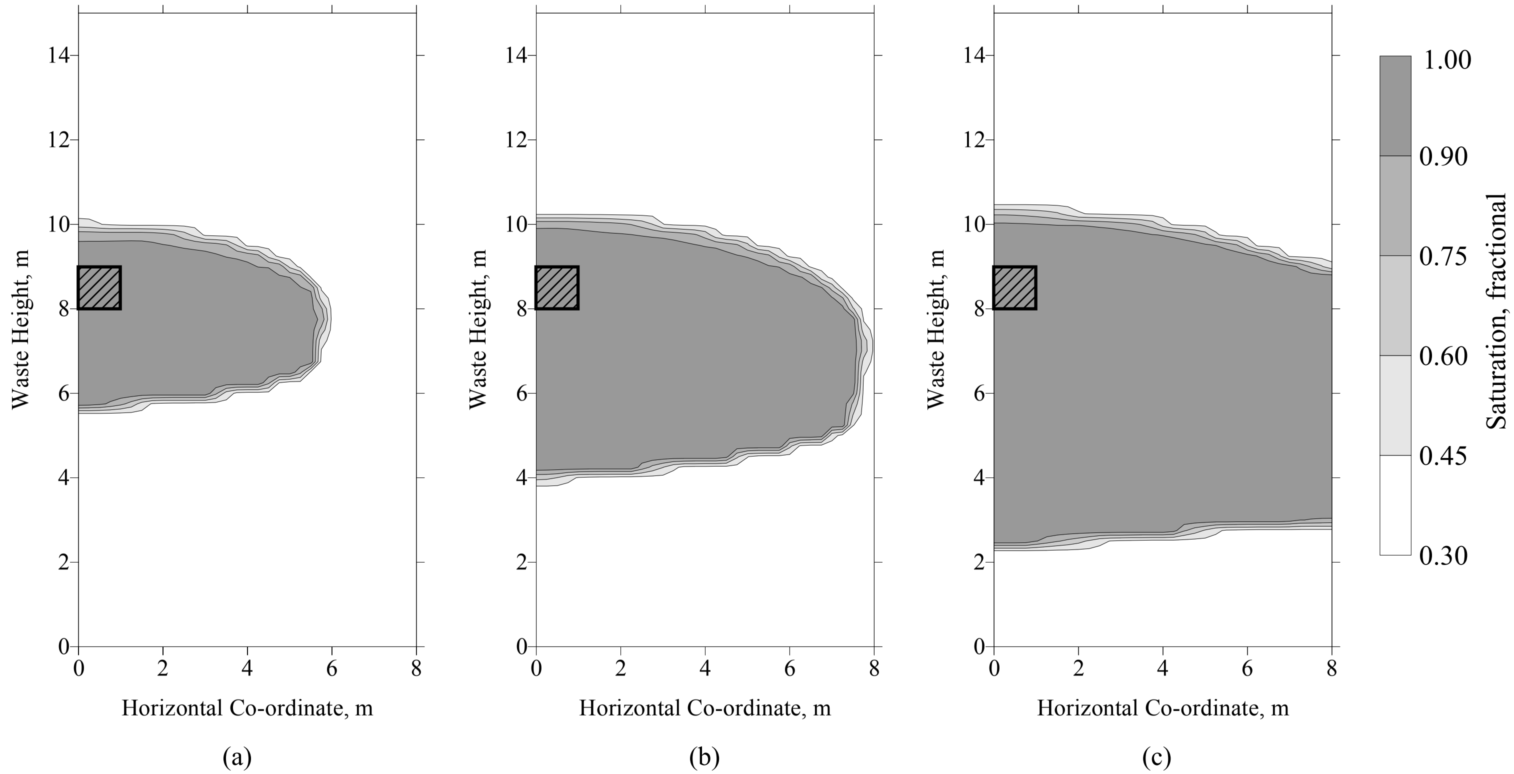


Figure 4.4.3. Leachate routing for an anisotropic waste mass with a longitudinal permeability of 10^{-4} cm/s and a transverse permeability of 10^{-3} cm/s after one (a), two (b), and three (c) weeks of operation. Leachate applied 8 hr per day at a rate of 2 m^3/m of trench/day.

4.5 Heterogeneous Waste Conditions

The exact nature and distribution of permeabilities in any particular landfill is difficult, if not impossible, to predict. However, it is useful to examine how the application of common probability distributions to permeability assignments affects leachate routing. The heterogeneous waste mass was modeled by breaking the waste matrix into 50 cm by 50 cm cross-sectional zones. Permeabilities were then specified for each of these zones using random numbers and probability density functions. Binomial, exponentially increasing, and exponentially decreasing probability density functions were successfully modeled. The binomial distribution case implies that most areas of the landfill are close to average with few pockets of loose as well as highly compacted areas. The exponentially increasing distribution implies a high probability of finding high permeability areas while the exponentially decreasing case indicates many low permeability areas with few high permeability areas. Either of the exponential distributions could be the result of large variations in the initial moisture content, waste characteristics, and compaction practices. Two permeability ranges, 10^{-1} to 10^{-5} cm/s and 10^{-2} to 10^{-6} cm/s, were simulated for each probability distribution. Although there are an infinite number of combinations of local permeabilities which could produce each of these distributions, only three sets of random numbers were used to simulate possible waste matrix characteristics. Thus, each probability density function was simulated using three potential waste matrixes generated by different random number sets. Leachate was applied intermittently, 8 hr per day, for an average rate of 4 m^3/day/m of trench.

For comparison purposes, figure 4.5.1 is presented which leachate routing after one week of applying leachate 8 hr per day at an average rate of 4 m^3/m of trench/day to homogeneous waste masses with permeabilities of 10^{-3} (Figure 4.5.1a) and 10^{-4} (Figure 4.5.1b) cm/s.

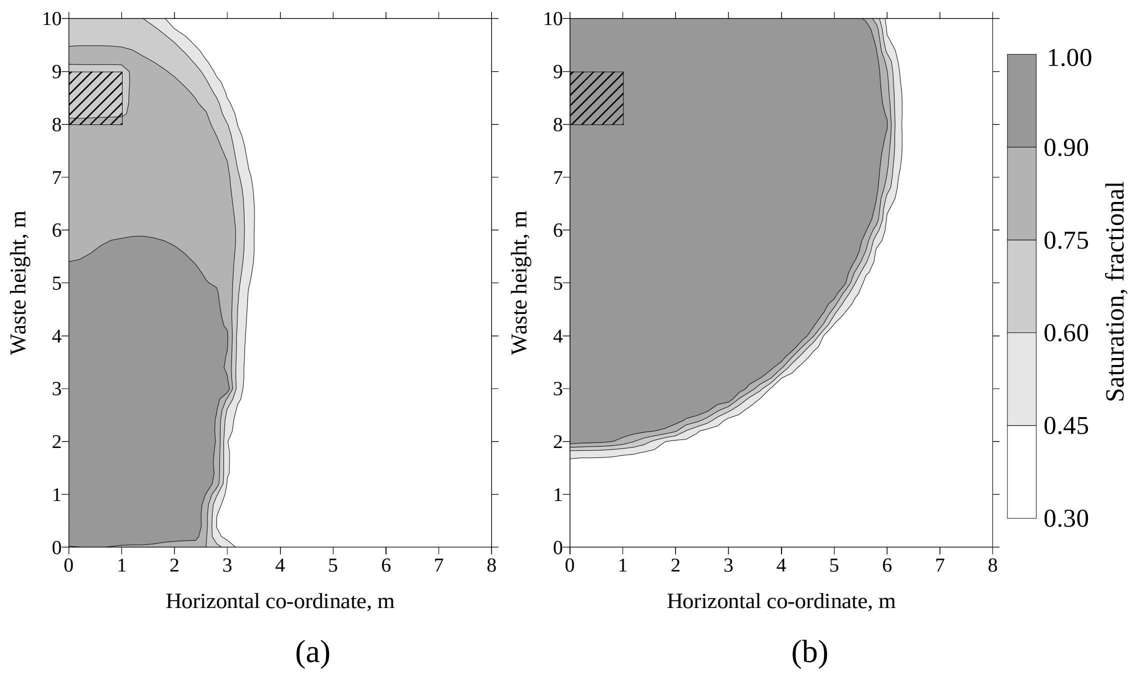


Figure 4.5.1. Comparison of leachate routing for homogeneous waste masses with permeabilities of 10^{-3} (a) and 10^{-4} (b) cm/s after one week of operation. Leachate applied 8 hr per day at a rate of 4 m^3/m of trench/day.

Figures 4.5.2 and 4.5.3 illustrate possible leachate routings after one week of applying leachate 8 hr per day at an average rate of 4 m^3/m of trench/day to a heterogeneous waste mass with a normal permeability distribution and average permeabilities of 10^{-3} cm/s

(Figure 4.5.2) and 10^{-4} cm/s (Figure 4.5.3). It is interesting to note, the normal distribution case with a mean permeability of 10^{-3} cm/s (Figure 4.5.2) results in increased lateral movement of leachate and decreased overall saturation. This effect on leachate routing suggests enhanced leachate storage opportunities potentially stimulating biological activity. The 10^{-4} cm/s mean permeability case differed from the homogeneous case in the shape of the saturation profile but, the waste mass was still predominantly saturated.

Figures 4.5.4 and 4.5.5 depict possible leachate routings after four days and one week, respectively, of applying leachate 8 hr per day at an average rate of 4 m^3/m of trench/day to a heterogeneous waste mass with an exponentially decreasing permeability distribution and median permeabilities of 10^{-3} cm/s (Figure 4.5.4) and 10^{-4} cm/s (Figure 4.5.5). The results for the waste mass with a median permeability of 10^{-3} cm/s simulation were presented at four days rather than one week due to the rapid leachate movement in this simulation. Leachate quickly piled up in the lower waste layers limiting the visual impact of the waste heterogeneities. Both figures show a high degree of preferential flow. Figure 4.5.4 shows rapid leachate movement with slight saturation increases and few pockets of highly saturated areas. Figure 4.5.5 again shows

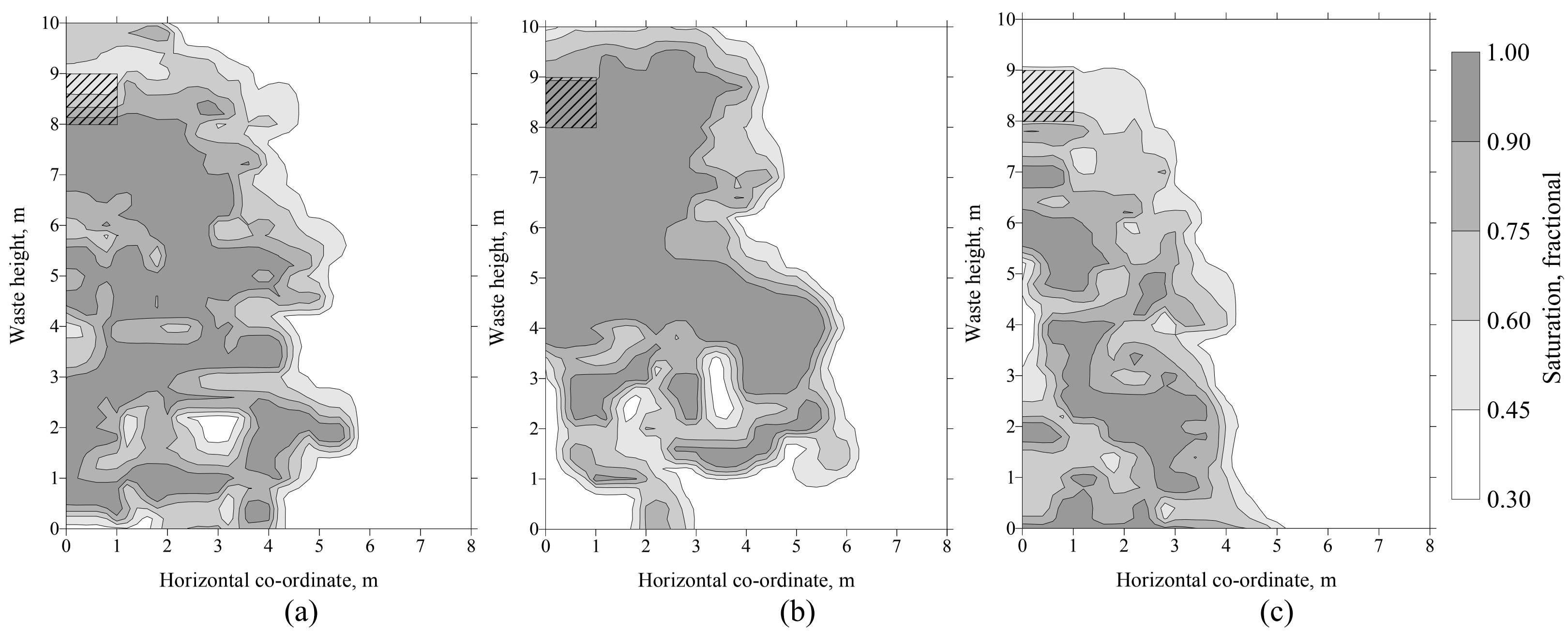


Figure 4.5.2. Three possible leachate routings after one week of leachate recirculation for a waste mass with a normal permeability distribution and an average permeability of 10^{-3} cm/s. Leachate applied 8 hr per day at an average rate of 4 m^3/m of trench/day.

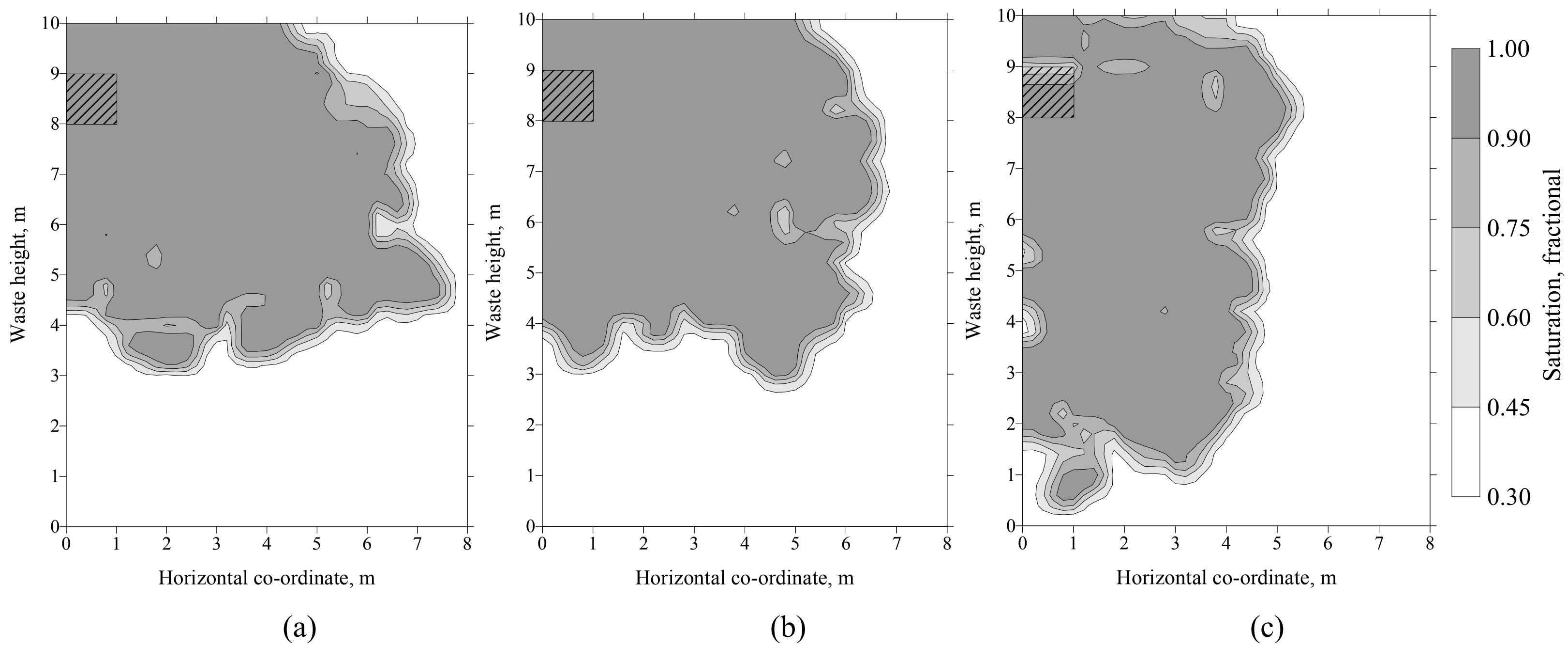


Figure 4.5.3. Three possible leachate routings after one week of leachate recirculation for a waste mass with a normal permeability distribution and an average permeability of 10^{-4} cm/s. Leachate applied 8 hr per day at an average rate of 4 m^3/m of trench/day.

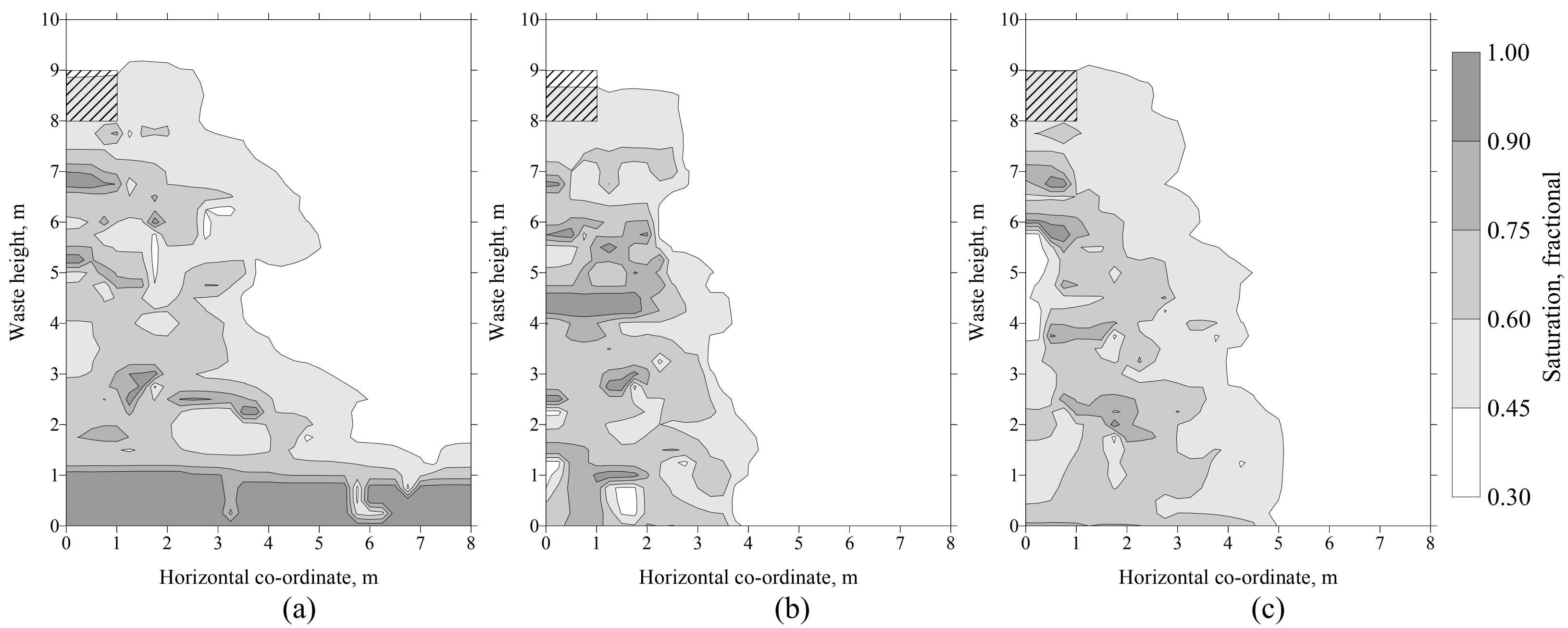


Figure 4.5.4. Three possible leachate routings after four days of leachate recirculation for a waste mass with an exponentially increasing permeability distribution and a permeability range of 10^{-1} to 10^{-5} cm/s. Leachate applied 8 hr per day at an average rate of 4 m^3/m of trench/day.

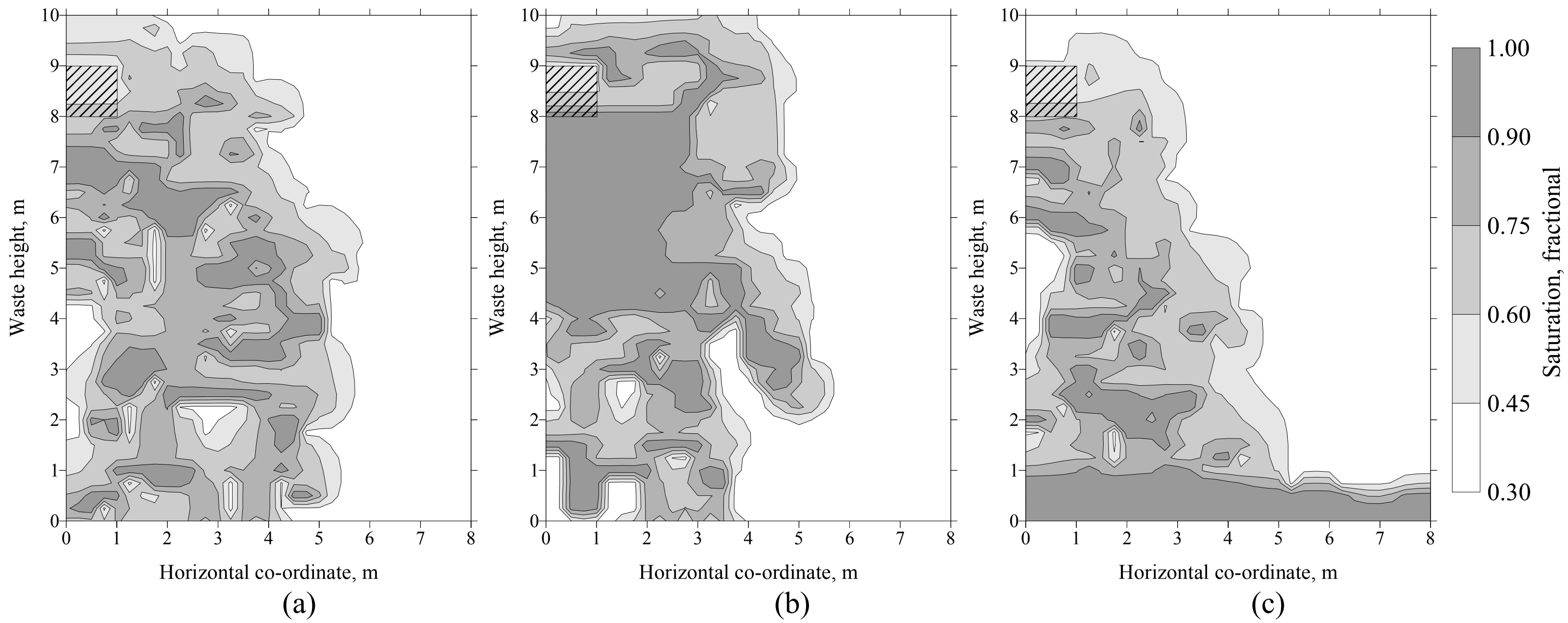


Figure 4.5.5. Three possible leachate routings after one week of leachate recirculation for a waste mass with an exponentially increasing permeability distribution and a permeability range of 10^{-2} to 10^{-6} cm/s. Leachate applied 8 hr per day at an average rate of 4 m^3/m of trench/day.

rapid leachate flow, although slower than in the previous case, saturation is greatly increased with numerous pockets and some larger areas of high saturation.

Figures 4.5.6 and 4.5.7 displays possible leachate routings after one week of leachate application 8 hr per day at an average rate of 4 m^3/m of trench/day to a heterogeneous waste mass with an exponentially increasing permeability distribution and median permeabilities of 10^{-3} cm/s (Figure 4.5.6) and 10^{-4} cm/s (Figure 4.5.7). The ability of leachate to move through the waste mass has been significantly limited in both cases. The area impacted by recirculation was predominantly saturated for both cases and, while more lateral spreading has occurred than in the homogeneous, normal distribution, or decreasing exponential distribution cases, the vertical movement of the leachate was seriously impeded. The high degree of saturation and impediment of vertical movement suggests that surface leachate seeps may develop. A comparison of the profiles to the 10^{-4} cm/s homogeneous waste mass case shows some variation in the shape of the saturation profile and flow around some low permeability, but the waste mass was still predominantly saturated and vertical leachate movement rates were similar.

As previously mentioned, the distribution of permeabilities within an actual landfill will be dependent upon the character of the waste, waste disposal operations including shredding and compaction, and the age of the landfill. Landfills which implement leachate recirculation, whether as a means to store leachate or enhance waste degradation, will be able to better realize their goals if the waste can be wetted in a uniform manner. Uniform wetting would be enhanced best by homogenizing the waste

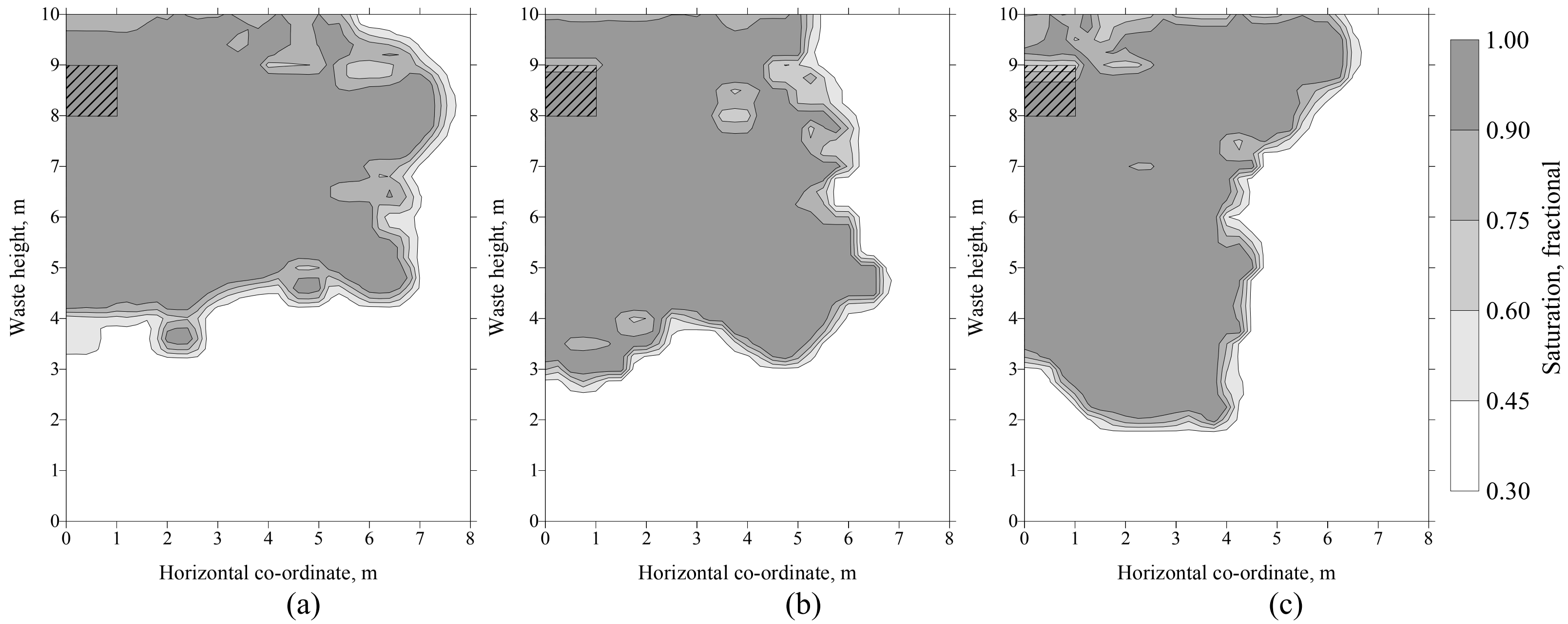


Figure 4.5.6. Three possible leachate routings after one week of leachate recirculation for a waste mass with an exponentially decreasing permeability distribution and a permeability range of 10^{-1} to 10^{-5} cm/s. Leachate applied 8 hr per day at an average rate of 4 m^3/m of trench/day.

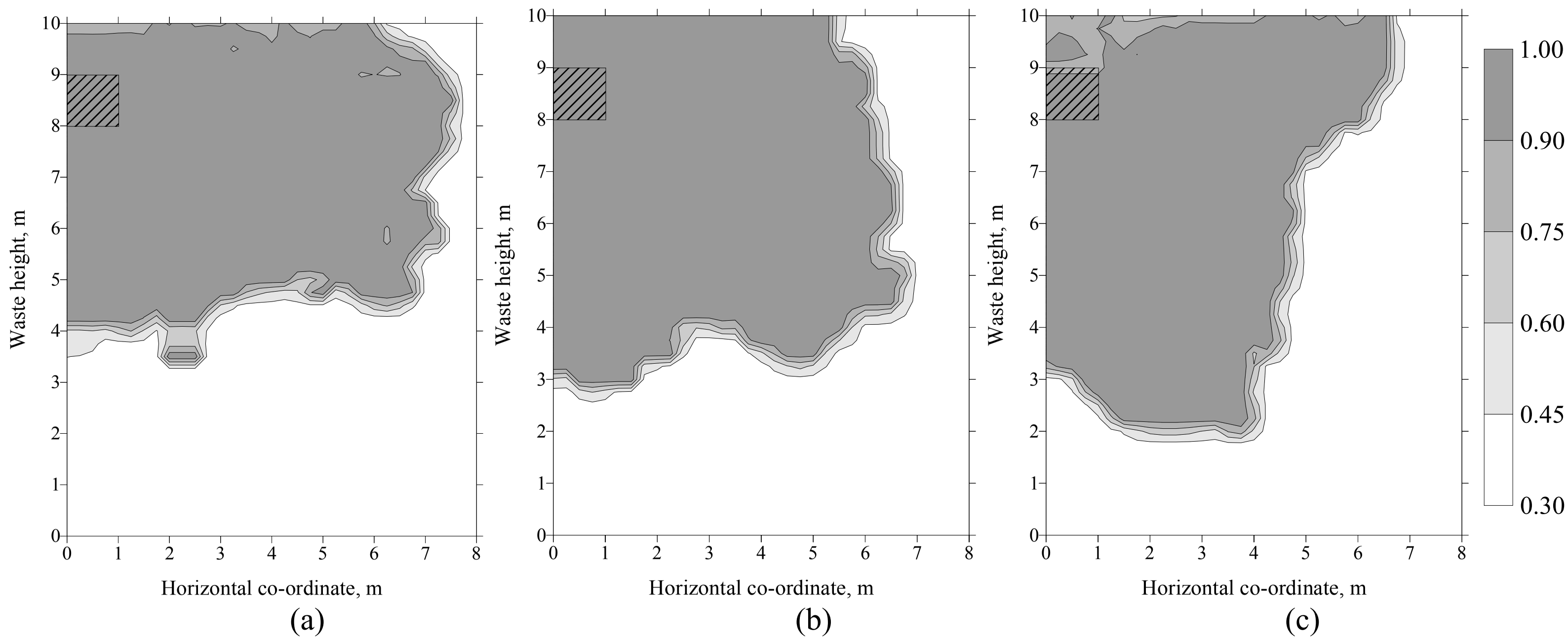


Figure 4.5.7. Three possible leachate routings after one week of leachate recirculation for a waste mass with an exponentially decreasing permeability distribution and a permeability range of 10^{-2} to 10^{-6} cm/s. Leachate applied 8 hr per day at an average rate of 4 m^3/m of trench/day.

mass and controlling the placement of low permeability materials within the landfill. Waste shredding would have the most significant effect on homogenizing the waste mass but may not be feasible at many sites. Bag breaking during placement and the removal of large, low permeability materials would be beneficial to sites which could not implement shredding.