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COMPARISON OF TWO APPROACHES TO MODELING MOISTURE MOVEMENT THROUGH MUNICIPAL SOLID WASTE*

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ABSTRACT

Channeled flow through municipal solid waste layers affects the time, rate, and amount of leachate generation. Leachate flow through the waste layers can be predicted either as a one-dimensional uniform Darcian flow through a homogeneous matrix layer or as a two-domain flow regime of channeled and matrix flows. This research project tests the performance of one-dimensional water balance models (HELP) and two-domain fractured-porous media flow models (PREFLO) by comparing calibrated predictions with experimental results for pilot-scale landfill leachate cells. The measured breakthrough time was much shorter than predicted by HELP. The measured cumulative leachate discharge volumes vary between 104 and 300 L. HELP and PREFLO models with default values predicted discharges to be zero and therefore significantly underestimated the actual discharges. When calibrated, both models provided much improved results. HELP approximated the time to effective storage and the leachate discharge with less than 30 percent difference. In the short term, modified parameter values can be used to improve leachate predictions. In the long term, a new model needs to be developed to predict the leachate flow through the waste layer.

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INTRODUCTION

Moisture movement through municipal solid waste (MSW) layers influences leachate generation and flow rate, waste moisture content, biodegradation, and settlement. The treatment of the waste layer as a homogeneous porous matrix material and the moisture movement as one dimensional Darcian flow in commonly used water balance models does not accurately represent the observed flow mechanism in solid waste layers. Due to the large particle size and particle size variation, flow channels form in interconnected macropores and lead to the rapid discharge of large leachate volumes. For the purposes of predicting moisture movement through large volumes of waste in landfills, two basic approaches exist to achieve more accurate leachate generation estimates: 1) Modify the one-dimensional flow water balance models with calibrated, spatially, and temporally averaged bulk parameters to reflect channeled flow, and 2) Apply a two-domain flow model to predict channeled and matrix flows (and their interactions) and calibrate the model with parameters for MSW.

The goal of this research is to evaluate these two approaches by, first, analyzing channeled flow in MSW as the theoretical basis for modeling flow. Then, the experimental measurement of the flow regime, key parameters, and leachate flows is conducted. Third, the leachate generation is predicted with the water balance and the two-domain models using, first, default values and, then, calibrated parameters. The results are then compared with the measured values to evaluate the performance and suggest the most appropriate method to predict leachate generation in waste layers.

Moisture movement through waste is often modeled as the unsaturated flow through a homogeneous porous matrix. Several researchers, however, have noted that channeling of moisture movement through MSW occurs and that the resulting moisture front is not uniform [1-3]. Channeling has been found to be significant on a pilot scale [4-6]. Therefore, a modified method of modeling moisture movement is required.

Channeled flow is defined as the preferred flow of leachate at significantly higher velocities than for homogeneous Darcian matrix flow. Therefore, unlike matrix flow, channeled flow cannot be described by a uniform moisture front. Instead the moisture front is "jagged" as moisture travels at a larger velocity in the channels than through the waste matrix, specifically when infiltration rates are greater than the matrix saturated hydraulic conductivity. Because flow is not uniform and velocities in the channels are high, channeling leads to shorter breakthrough times, lower moisture storage, greater leachate discharge rates, and shorter duration of events than would be expected if the media were homogeneous [5, 6].

Shorter breakthrough times result from moisture flowing through channels and being conveyed deeper into the waste column in a shorter period of time than if the moisture was being conveyed through the waste matrix. Therefore, moisture in channels will break through the column sooner than moisture traveling through the matrix. Because moisture travels faster through the waste, and breakthrough is experienced sooner, less moisture has to be added to the waste before breakthrough occurs. The moisture content of the waste at which drainage first occurs has been called the practical field capacity [5]. The practical field capacity FC_p is less than the conventional field capacity, which is the moisture content at which an initially saturated porous medium stops draining. The difference between the two moisture contents arises from measurement of field capacity. For an initially saturated media, all pores including channels are filled. The large pores drain first followed by the smaller pores. However, some pores remain filled with water after free gravity drainage ceases. For the determination of practical field capacity, the medium is initially unsaturated. When water is added, it is conveyed through channels as well as the matrix, and, therefore, breaks through the medium faster because of the channeled flow. This results in a lower moisture content at practical field capacity than at conventionally defined field capacity.

Channeling affects the level of the effective storage ES, (the ultimate moisture content) and the time until it is reached, t_{ES}. While channels form at low initial moisture contents (practical field capacity), the recurring flow will lead to redistribution from the channels into the matrix, driven by the capillary pressure in the small pores. Thus, some infiltration will be added to storage until the ultimate effective moisture storage ES is reached at time t_{ES}, later than the breakthrough time t_{bt}. The cumulative leachate discharge Q will reflect channeled flow and moisture redistribution. Initially, discharge will start very quickly, and then only slowly increase as moisture is redistributed and stored until, ultimately, all added moisture is discharged. Channeling also affects the duration of leachate drainage t_Q. Because the flow through channels is faster than the matrix, a leachate event will start sooner and tail off more quickly in channeled flow. If flow were through the matrix only, the flow rate out of the waste, as well as the time of the drainage event would depend on the hydraulic conductivity of the matrix.

In the following, the theory of unsaturated flows in one-dimensional water balance and two-domain matrix-fracture flow models is analyzed. The findings suggest hypotheses about the performance of the two approaches to predict initial breakthrough time t_{bt}, time to reach ultimate effective moisture storage t_{ES}, cumulative leachate discharge Q, and duration of the discharge t_Q.

Several past attempts at leachate prediction have used the water balance method to determine the volume of leachate draining from a waste column [see e.g., 7]. Typically water balance models do not account for the mechanisms of moisture movement. Instead, they indirectly estimate leachate percolation through MSW [8]. A water balance is performed by setting water inputs into the waste equal to the sum of all water outputs plus the change in storage of water in the waste. The result provides the magnitude and direction of the moisture flux.

A refined and commonly used water balance model, the Hydrologic Evaluation of Landfill Performance (HELP) model [9], couples the water balance method with one dimensional Darcian moisture movement through the waste. A water balance is first used to estimate the amount of water available for infiltration and this water is then added to the moisture content in the waste matrix. HELP specifies default values for the moisture content and other properties of the waste, but also allows these parameters to be specified by the user. The HELP model along with other one-dimensional transport models assume the waste to be a homogeneous porous medium with a defined hydraulic conductivity, changing moisture content and a defined relationship between these two variables throughout the waste column [10]. The estimates of specific parameter default values may not accurately represent MSW. However, spatially and temporally averaged parameters can be modified to reflect moisture movement mechanisms such as channeling. Using HELP as an example of a typical one domain water balance model it is possible to examine how these models represent moisture movement.

Flow through the waste is represented by Darcy's Law. Darcy's Law can only be used if the flow is laminar (because it assumes a linear relationship between head loss and velocity) and controlled by viscous forces [11]. These conditions are assumed to occur in a porous matrix if the Reynolds number is below values of 4 to 10 [12]. If the Reynolds number is above 10, inertial forces due to higher velocities can no longer be neglected, and Darcy's Law cannot be used to represent the flow.

Though Darcy's Law was originally developed for saturated flow, it can be used for unsaturated conditions by expressing the hydraulic conductivity as a function of the suction head.

$$q = -K(\Psi)\Delta(h) \tag{1}$$

Equation (1) simplifies to Darcy's law when the flow is considered one-dimensional and the medium is saturated ($\psi = 0$). A solution for equation (1) requires that the relationship between K and ψ be known. The unsaturated drainage equation of HELP uses both the Brooks-Corey relationship (eq. 2), and the Campbell equation (eq. 3) to relate K and ψ indirectly by making both a function of the moisture content of the porous matrix, θ [9] (eq. 4).

$$\frac{\theta - \theta_r}{n - \theta_r} = \left(\frac{\Psi_b}{\Psi}\right)^{\lambda} \tag{2}$$

$$K = K_s \cdot \left(\frac{\theta}{\theta_s}\right)^{3+\frac{2}{\lambda}} \tag{3}$$

$$q = K_s \cdot \left[\frac{\theta - \theta_r}{n - \theta_r}\right]^{3+\frac{2}{\lambda}} \cdot \frac{dh}{dl} \qquad (4)$$

Equation 4 represents moisture movement as plug flow because K_s, θ, n, and λ are constant through the medium and can be further simplified by setting the hydraulic gradient to unity [9]. The HELP model, like other water balance models, does not consider the effects of capillarity on the unsaturated flow rate. Therefore, unsaturated drainage flow occurs only when the moisture content of a layer has reached field capacity (provided that no underlying layer has a lower moisture content than the layer in question) [9]. This implies that drainage from a layer with a low field capacity should occur earlier than from a layer with a high field capacity.

Three discrepancies may affect the accuracy of HELP predictions. First, unsaturated flow may occur in some channels before the field capacity of the whole layer is reached. Second, HELP defines field capacity as the water-filled fraction of the waste volume when free drainage from a saturated waste matrix just ceases. Unsaturated flow at moisture contents below field capacity is neglected unless the moisture content of the underlying layer is lower [13-15]. Practically, however, the moisture content in the waste never reaches saturation. Rather, the moisture content increases until the point where free drainage begins. This moisture content on the wetting curve is defined as the practical field capacity FC_P [6]. This definition takes into account the practical reduction of the field capacity due to channeled flow. Third, once field capacity is reached, moisture storage may continue to increase in the waste layer through redistribution of water from flow channels into the porous matrix. Thus, the practical field capacity only defines the moisture content at the beginning of leachate drainage. After drainage begins, additional moisture is stored until a condition of constant moisture content is reached when the leachate discharge rate equals the infiltration rate. This ultimate moisture content we have called "effective storage" (ES).

Channeling has been shown to be a significant mechanism of flow through MSW. Channeling may be represented implicitly in HELP by decreasing the field capacity and increasing the saturated hydraulic conductivity (used in eq. 4).

In contrast, the matrix and channel components of flow through MSW may also be represented explicitly by two-domain fractured-porous media models. These models treat the flow domains in channels and matrix separately and account for the exchange of flow between domains [16-18]. Two domain models better represent channeled (laminar of turbulent) flows separately from Darcian flow in the matrix. Some parameters, such as the exchange term between the two domains, however, may be difficult to determine [19]. Many two-domain fractured-porous media models exist for fractured rock and macroporous soil. However, none have yet been developed for MSW. Because both domains are explicitly represented, these models should provide accurate prediction of breakthrough time, time to steady state, volume of leachate discharged, and duration of leachate discharge. A representative two-domain model describing unsaturated flow is PREFLO [20]. PREFLO was selected by evaluating several two-domain models to determine the model which was most applicable to predict flow through MSW (see [4] for ranking criteria and evaluation results). The model allows actual channel parameters, such as the channel diameter, to be defined. Therefore, it may simulate the physical mechanisms more accurately than other models.

PREFLO initially routes precipitation as infiltration into the porous matrix. Then if ponding occurs, the excess precipitation is infiltrated as preferential flow into the macropores. PREFLO routes water through the porous matrix using the Richards Equation with sink terms for water removal by roots, addition of water from channels, and removal or addition of water from boundaries.

$$\partial\theta/dt = \Delta(K(\Psi)\Delta(h)) - R(h,z,t) + PF(h,z,t) - BC(h,z,t) \tag{5}$$

If precipitation intensity is greater than the saturated hydraulic conductivity of the matrix, flow is routed through the macropores or channels of the soil according to Poiseuille's Law

$$Q_p = \frac{\pi \rho g r^4}{8\mu} \tag{6}$$

Liquid can also be transferred from the channels to the matrix according to Darcy's Law (1) accounting for the head difference between the channel and the matrix [20]. Equation 6 assumes that the flow through the channels is laminar. Water percolating through the channels is infiltrated laterally into the soil matrix with Darcy's Law

$$Q = 2\,\pi\,r\,z_i\,K(h_{i,j})\,\frac{(hp - k_{i,j})}{x_p} \tag{7}$$

Originally, PREFLO modeled drainage to a water table, so the lowest suction pressure occurred at the bottom node of the profile. However, the model was modified to describe free drainage conditions with uniform capillary pressure specified throughout the profile. The initial hydraulic gradient at the start of the simulation is, therefore, non-zero. Due to the change in initial conditions, it was also necessary to modify the drainage routine. Drainage out of the matrix of a profile occurred only when the bottom node reached a suction pressure of zero. These changes allow PREFLO to more accurately represent the experimental conditions used in this research.

While PREFLO considers channeled flow and the exchange between the channel and matrix (as do other two domain models), HELP (and other water balance, one domain models) consider only flow through a homogeneous matrix. Table 1 shows the main differences between these two modeling approaches.

Table 1. Main Differences between One Domain and Two Domain Modeling Methods

Factors	HELP (water balance method)	PREFLO (two-domain)
Representation of Physical System	One dimensional homogeneous porous medium	Homogeneous matrix and large channels throughout matrix
Representation of Moisture Movement Mechanisms	Darcian flow through medium	Darcian flow through medium, laminar flow through channels, exchange between channels and matrix based on head differences
Commonly Used Approach for MSW	HELP and other water balance models are commonly used	This approach has not yet been tried for MSW
Data Requirements	Require climactic data as well as bulk MSW parameters such as porosity, field capacity, pore size distribution, and hydraulic conductivity (wide range of literature values available)	Require climactic data as well as bulk MSW parameters and specific parameters such as channel diameter, length, and spacing (not widely available)
Prediction of Leachate Flow Parameters		
— Breakthrough time t_{bt}	— Accurate, if the correct field capacity and hydraulic conductivity are used	— Accurate if the infiltration is routed into the channels
— Time to effective storage t_{ES}	— Accurate if the correct ultimate effective storage is used	— Possible if the moisture is redistributed accurately
— Cumulative volume Q	— Accurate if the correct ultimate effective storage is used, but may overestimate Q if the practical field capacity is used	— Possibly as good as HELP if the matrix storage and redistribution are specified accurately
— Duration of flow t_Q	— Likely to overestimate because of the different levels of moisture content at the beginning and the end of drainage	— Accurate if the channel and matrix parameters can be determined

From Table 1 it is then possible to hypothesize outcomes of moisture movement simulations for both models. HELP should predict a higher breakthrough time than PREFLO because channels are not considered. Therefore, moisture is routed through the matrix at a velocity less than the channeled flow velocity. Further, PREFLO considers both flow domains and the exchange of water between domains, resulting in a more accurate prediction of moisture contents and time to reach steady state. The HELP model may overestimate or underestimate leachate volumes depending on the level of the threshold moisture storage. This value can be selected to reflect the beginning of drainage at the practical field capacity or the attainment of the ultimate discharge at the effective storage. Once set, this value determines the moisture content at which drainage will start and to which the entire waste column drains. The duration of leachate flow may also be overestimated by the HELP model because flow rate through the waste will be limited and the threshold moisture content by the hydraulic conductivity and the threshold moisture storage of the matrix. PREFLO however, should predict duration accurately because drainage will occur more quickly if channels are considered and will last longer if matrix flow is considered. Overall, the PREFLO model should more accurately predict the above parameters because it more accurately represents moisture movement through MSW.

METHODOLOGY

The experiments were designed to accomplish three research objectives: 1) to confirm channeling, 2) to characterize the flow regime in pilot scale waste cells, with the key flow parameters of practical flow cross-sectional area A, practical field capacity FC_P, pore size distribution index λ, effective storage ES, apparent hydraulic conductivity K'_{us}, breakthrough time t_{bt}, time to effective storage t_{ES}, cumulative discharge Q, and duration of flow event t_Q, and 3) to compare the prediction of the water-balance HELP method and the two-domain PREFLO method with the measured leachate flows.

Eight rectangular steel containers with dimension of 1.8 m length by 1.6 m width by 1.5 m height were used as pilot scale cells. The equivalent diameter of the cells was therefore over twenty-five times the average Rosin-Rammler particle size and exceeded the minimum ratio of 5:1 to prevent wall effects on flow and settlement [21]. The instrumentation consisted of tensiometers and flow sensor grids to investigate channeling. Discharge collection containers were used to determine breakthrough time and discharge. Each cell was constructed, from bottom up, with 1) a PVC liner, 2) a flow sensor grid, 3) municipal solid waste, 4) tensiometers, 5) irrigation hose, and 6) a PVC cover. A grid of twelve flow sensors was placed in the bottom of the cell to measure the flow rate and cross-sectional area of flow. The spatial and temporal differences in the discharge rates (as measured with the flow sensors) were used to test for channeled flow and to describe the flow pattern.

A 2^2 factorial design was used in this study. The two experimental factors were infiltration rate and waste bulk density. Each factor was set at two levels, high and low. The high level of infiltration intensity was set at 18 to 25 mm/hr, which corresponds to the ten to fifteen year one- hr. storm event, while the low level was set 7 to 15 mm/hr to correspond to a two year-one hr storm event in Edmonton [22]. The high density cells were compacted to 600 kg/m^3. This value corresponds with good landfill compaction [23], and is often achieved at large, modern landfills [24]. The low density cells were compacted to approximately 300 kg/m^3, a value that corresponds with the densities in landfills with low compaction [2]. Waste characteristics, unsaturated flow parameters, and leachate discharges in the pilot cells were measured.

The prediction of leachate flow variables t_{bt}, t_{ES}, Q, and t_Q were first accomplished with HELP and PREFLO default parameters. Then, the key parameters were determined with sensitivity analyses. For these parameters, the values were calibrated with the measured values. Then, a second set of predictions was generated and plotted. These results were then compared with the measured leachate flow results to test the models' performance.

RESULTS

Waste Particle and Pore Sizes

Rosin-Rammler particle size values for raw municipal solid waste reported in the literature range from 8.9 to 17.8 cm [25]. Previous studies of leachate flow used waste with a mean X_0 of 9.0 cm and a standard error of 3.14 cm [6]. The characteristic particle sizes for the unshredded waste used in this experiment averaged 7.3 cm with a standard error of 0.5 cm and were therefore similar to reported raw waste particle sizes and slopes. The Rosin-Rammler slope n for raw waste is reported as 1.17 to 1.33 in the literature [25] and as 1.1 with a standard error of 0.09 in previous, similar experiments [6]. The slope n for wastes in this test average 1.3 with a standard error of 0.04 and were therefore similar to other tested wastes.

The porosity values for waste as obtained from the literature [2, 6] show values between 0.4 and 0.58. The HELP model uses default values of 0.67 or 0.17. Here, 0.67 is used in the default prediction, while the previously measured value of 0.52 is used in the calibrated predictions. Similarly, the pore size distribution index λ is reported at values between 0.45 and 0.65. Here, these values are used in the default and calibrated predictions, respectively.

For the two-domain model, pore diameters averaged 1.9 cm with a range from 1.6 to 2.2 cm. From the pore diameter, the Reynolds number for channeled flow could be determined for the eight test cells with a mean value of 9.4 and a range of the means from 5.4 to 13.4. In five cells, the critical upper Re value for Darcian flow of 10 was exceeded and indicated that non-Darcian flow occurred.

Flow Area and Flow Parameters

The moisture flow patterns were analyzed with the measurement of the active flow area.

The cross-sectional area where active flow takes place is expected to be substantially less than the cross-section of the waste in the cells. At breakthrough, when the practical field capacity is just reached, the average flow area is 21 percent of the total cross-section. The area is smaller (12.5%) for the high infiltration cells and larger (29%) for the low infiltration cells. At ultimate discharge, when the moisture content is at effective storage, the flow area has increased to 39 percent on average and the values for low and high infiltration are closer. The overall average active flow area is 30 percent of the cross-section. These values are very close to the value of 25 percent measured in previous lab cells [5, 6]. The value of 25 percent is also implicitly the active flow area used in the default values for the HELP model's new MSW layer #19 with channeling [9]. For the predictions here, the value of 25 to 30 percent is assumed to hold.

The practical field capacity FC_p, initial unsaturated hydraulic conductivity $K'_{us\text{-}init}$ and the breakthrough time t_{bt} are all associated with the beginning of leachate flow (see Figures 1 and 2, at t_{bt}). The results are shown in Table 2 for all experimental cells, along with the means and standard deviations. Infiltration rate and waste density were discussed in the experimental design.

The practical field capacities FC_p of all cells are very tightly distributed around the mean of 0.12, with a standard error of 0.006, for a 95 percent confidence range of 0.108 to 0.132. The mean is therefore not significantly different from previous experimental values of 0.1 to 0.13, but is lower and higher, respectively, than the two HELP default values of 0.292 (for layer type 18) and 0.073 (for layer type 19). More importantly, though, the practical field capacity does not vary significantly with infiltration rate or waste density.

The breakthrough times t_{bt} for six of eight cells are very short and very consistent at fifteen to thirty minutes (see Table 2 and Figures 1 and 2). Two low infiltration cells, however, exhibited two orders of magnitude higher breakthrough times at twenty-five and forty hours. The two high values skew the distribution, but show that specific wastes may slow the flow velocity. The breakthrough times are, however, still significantly lower than predicted and are very close to the previously determined values [6]. Even the higher values are an order of magnitude lower than the predicted breakthrough time of one and one-half years (548 days, or 788,400 minutes) with the HELP default values for MSW layer (#19) with channeled flow.

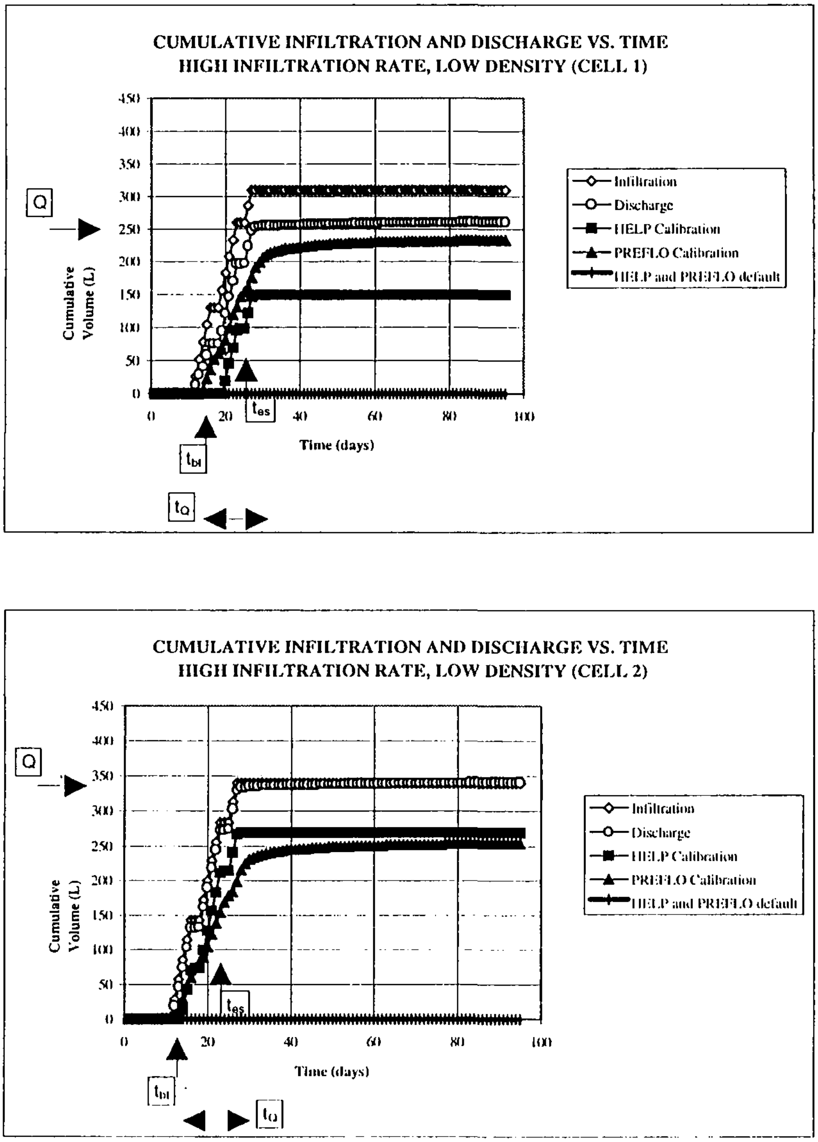
The redistribution and additional storage of moisture after breakthrough is by the differences between the cumulative infiltration and discharge curves shown (in Figures 1 and 2). The effective moisture storage increases noticeably between breakthrough time and the time to effective storage for the low infiltration cells (as compared to the high infiltration rate cells) and less so for the high density cells (as compared to the low density cells). Most significantly, the two low infiltration—high density cells (#7 and #8) show a significant increase in moisture content from the practical field capacity FC_P of 0.13 to the effective storage ES of 0.2 to 0.23 (see ES values in Table 2). ES can be viewed as the difference between infiltration and discharge (plus initial moisture content) at the time to effective storage (t_{ES} in Figures 1 and 2). The differences between field capacity FC_P to effective storage moisture content ES basically reflect the moisture redistribution into the smaller pores and the storage therein. The result is the increase in moisture content of the waste until a constant discharge condition is reached when discharge equals infiltration rate.

The cumulative discharges Q from the cells represent the total leachate volume produced during the experiments, that is, between the beginning of infiltration and the time when constant discharge was reached at effective storage (see Figures 1 and 2 and Table 2). The values for the high infiltration rate cells range between 234 and 339 L with an average of 269 L compared with the low infiltration cells' discharges of between 89 and 244 L and an average of 135 L. Therefore, as is apparent from the graphs, the cumulative discharge of the low infiltration rate cells was lower and resulted in higher moisture storage by approximately 134 L per cell, which translates into the higher effective storage values of 0.22 for the low infiltration cells (compared with 0.15 for high infiltration cells). The slow increase of the discharge curves further shows that moisture redistribution is occurring from the channels into the matrix material. In contrast, the high infiltration cells reach constant discharges more rapidly (at 2 to 15 days) and store less moisture at ES of 0.15. Similarly, the duration of the flow events t_Q from the start to the end of discharge is shorter for high infiltration and longer for low infiltration rates.

In summary, the experimental results for key flow parameters are consistent with previously measured values and confirm the effects of channeled flow on lower practical field capacity FC_P, lower breakthrough time, and higher hydraulic conductivity. Further, the ultimate effective moisture storage ES is significantly higher than the practical field capacity FC_P.

Higher infiltration rates reduce breakthrough time and effective storage ES increased densities increase field capacity FC and effective storage ES. The results therefore support the hypotheses that slow infiltration rates and higher waste densities will lead to longer breakthrough times and increase the moisture storage capacity of the waste.

HELP and PREFLO predictions were carried out with default values and resulted in zero leachate generation as shown by the horizontal discharge curves in Figures 1 and 2. The parameter values were then calibrated with the experimental results as summarized in Table 3. Principally, the moisture storage (denoted in the models as the field capacity) was increased by a factor of 1.5 to the level of the measured effective storage. Further, the apparent hydraulic conductivities were adjusted up to 2.2 cm/s for HELP to reflect channeling, and down

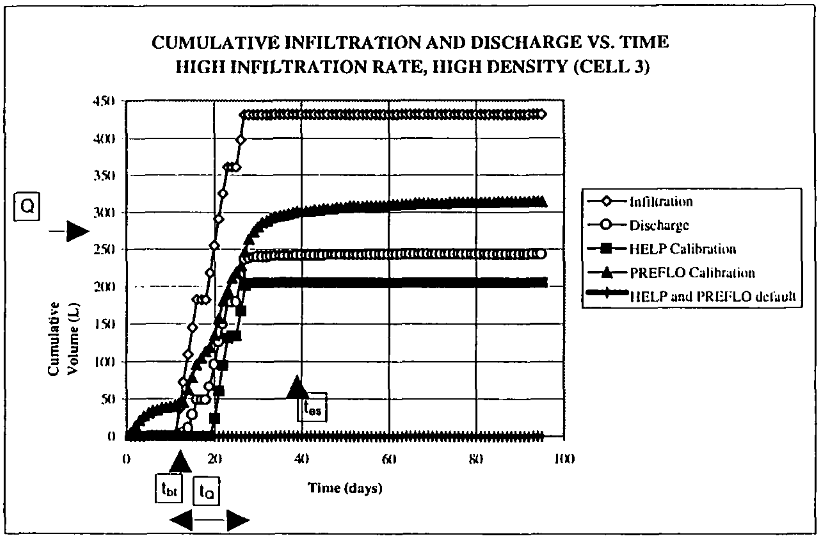


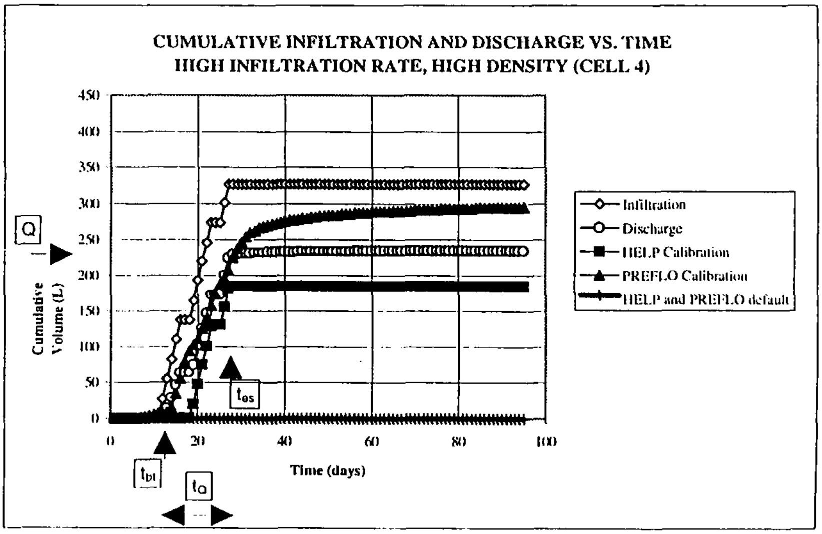
CUMULATIVE INFILTRATION AND DISCHARGE VS. TIME
HIGH INFILTRATION RATE, LOW DENSITY (CELL 1)

CUMULATIVE INFILTRATION AND DISCHARGE VS. TIME
HIGH INFILTRATION RATE, LOW DENSITY (CELL 2)

High Rate - Low Density Cells 1 and 2

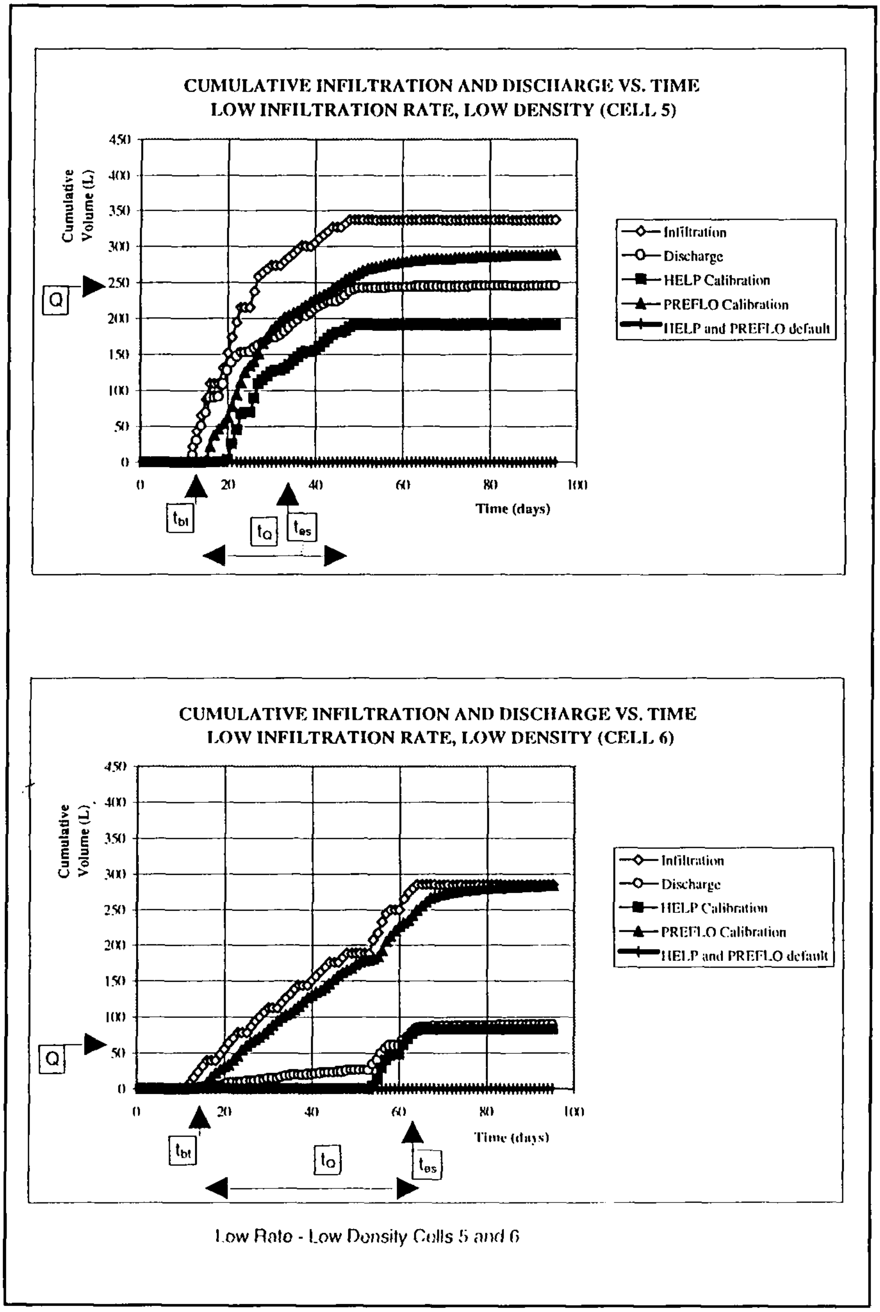
Figure 1. High infiltration rate results.


CUMULATIVE INFILTRATION AND DISCHARGE VS. TIME
HIGH INFILTRATION RATE, HIGH DENSITY (CELL 3)


CUMULATIVE INFILTRATION AND DISCHARGE VS. TIME
HIGH INFILTRATION RATE, HIGH DENSITY (CELL 4)

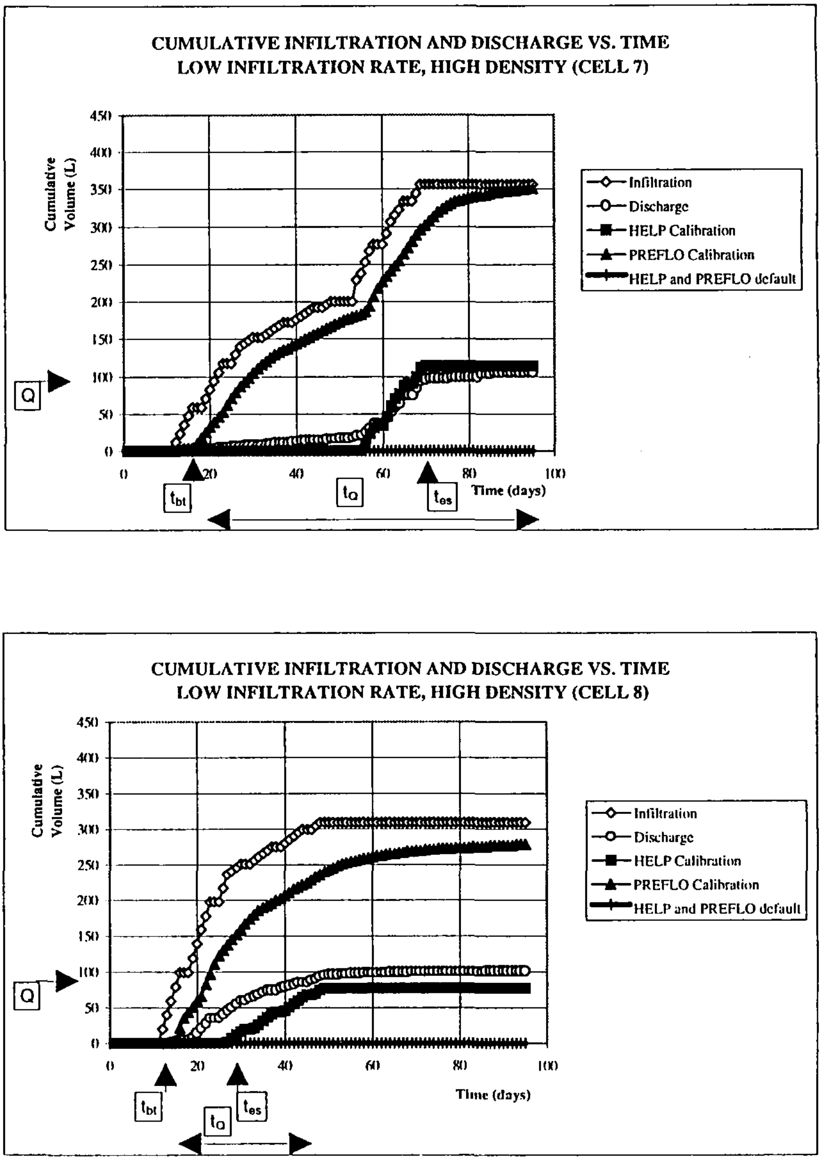
High Rate - High Density Cells 3 and 4

Figure 1. (Cont'd.).



Low Rate - Low Density Cells 5 and 6

Figure 2. Low infiltration rate results.



Low Rate - High Density Cells 7 and 8

Figure 2. (Cont'd.).

Table 2. Pilot Cell Waste and Flow Parameter Results

	High Infiltration Rate			
	Low Density		High Density	
Parameters	Cell 1	Cell 2	Cell 3	Cell 4
Cell Density [kg/m^3]				
– initial	323	298	420	458
– final	522	484	539	532
Initial Moisture Content [–]	0.08	0.08	0.11	0.12
Field capacity practical FCp* [–]	0.113	0.105	0.126	0.133
Infiltration rate until $t=t_{bt}$ (mm/day)	9.0	9.8	12.8	9.6
Discharge rate until $t=t_{bt}$ (mm/day)	0.20	0.26	0.06	0.09
Breakthrough time t_{bt} [min]	15	15	20	15
Hydraulic conductivity — initial K'_{us} [cm/s]	$1.02 \cdot 10^{-2}$	$9.0 \cdot 10^{-3}$	$9.7 \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$
Infiltration rate at $t=t_{ES}$ (mm/day)	9.1	9.6	12.8	9.6
Discharge rate at $t=t_{ES}$ (mm/day)	9.1	9.5	12.7	9.6
Effective storage ES [–]	0.14	0.11	0.19	0.17
Time to Effective Storage t_{ES} (days)	9	2	15	15
Hydraulic conductivity — ultimate K'_{us} [cm/s]	$1.05 \cdot 10^{-5}$	$1.13 \cdot 10^{-5}$	$1.48 \cdot 10^{-5}$	$1.11 \cdot 10^{-5}$
Cumulative Discharge Q [L]	260	339	243	234
Duration of the flow event t_Q [days]	17	17	17	17

Low Infiltration Rate				All Pilot Cells		
Low Density		High Density				
Cell 5	Cell 6	Cell 7	Cell 8	Mean	Std. Deviation	Std. Error
267	353	445	432	374.5	73.5	26.0
413	607	492	504	511.6	55.2	19.5
0.07	0.09	0.11	0.11	0.1	0.02	0.007
0.09	0.13	0.133	0.132	0.12	0.016	0.006
7.4	4.1	3.3	7.0	7.9	3.1	1.1
0.15	0.001	0.001	0.002	0.1	0.1	0.04
15	1485	2880	30	559	1069	371
$8.4 \cdot 10^{-3}$	$1.2 \cdot 10^{-4}$	$7.6 \cdot 10^{-5}$	$6.9 \cdot 10^{-3}$	$7.3 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$
1.8	2.1	3.8	1.7	6.3	4.4	1.6
1.8	2.1	3.8	1.7	6.3	4.4	1.6
0.15	0.29	0.24	0.20	0.19	0.06	0.02
23	54	53	18	24	19	
$2.09 \cdot 10^{-6}$	$2.43 \cdot 10^{-6}$	$4.42 \cdot 10^{-6}$	$1.98 \cdot 10^{-6}$	$7.33 \cdot 10^{-5}$	$5.13 \cdot 10^{-5}$	$1.78 \cdot 10^{-5}$
244	89	106	101	202	91.6	32.4
39	55	75	39	35	21.8	7.7

Table 3. Flow Parameters for HELP and PREFLO Predictions of Leachate Generation

Flow Parameter	Default Values	Calibrated Parameters	Rationale
Daily Infiltration [mm]			These values were determined by the experimental design of the pilot cells and remained constant
Layer Thickness [cm]	99	99	
Initial Moisture Content [–]	0.11	0.11	
HELP Parameters			
Porosity [–]	0.67	0.52	Experimental porosity was repeatedly determined to be 0.52
Saturated Hydraulic Conductivity [cm/s]	1×10^{-3}	2.2	The calibrated value of 2.2 cm/s was backcalculated from the measured apparent unsaturated hydraulic conductivity at breakthrough with the Campbell equation with a pore size distribution index value of 0.65
Field Capacity [–]	0.292	1.5 · FCp	The value of the effective storage ES (= 1.5 FCp) was substituted for the “field capacity” to reflect the ultimate moisture content in the waste layer at constant discharge
Pore Size Distribution Index [–]	0.45	0.65	The experimentally determined value of 0.65 was substituted for the default value of 0.45
PREFLO Parameters			
Porosity [–]	0.67	0.52	Experimental porosity was determined to be 0.52
Saturated Hydraulic Conductivity [cm/s]	1×10^{-3}	$1.0 \cdot 10^{-5}$	The calibrated value of 2.2 cm/s was backcalculated from the measured apparent unsaturated hydraulic conductivity at breakthrough with the Campbell equation with a pore size distribution index value of 0.65
Pore Size Distribution Index [–]	0.45	0.65	The experimentally determined value of 0.65 was substituted for the default value of 0.45
Pore Area [%}	2.0	2.0	The measured value for solid waste was applied

to 1.10^{-5} cm/s for PREFLO to force flow through the channels rather than through the matrix.

The calibrated prediction results and the comparison with measured results are shown in Figures 1 and 2 and Table 4. The breakthrough times t_{bt} are vastly overpredicted by HELP and slightly under to overpredicted by PREFLO. HELP underpredicts by 50 percent to 9 percent, while PREFLO overpredicts t_{ES} (i.e., never reaches effective storage) for high infiltration and underpredicts t_{ES} for low infiltration rates the time to effective storage t_{ES} is underpredicted. The leachate discharge is slightly underpredicted by HELP by minus 31 percent to minus 3 percent, and slightly under- to overpredicted by PREFLO. Finally, the duration of the flow event is consistently underpredicted by HELP and overpredicted by PREFLO.

Overall, the predictions with default values are zero and therefore do not match the observed behavior. With calibrations, the HELP model moderately underpredicts the time to effective storage, the cumulative discharge and the duration of the flow event. HELP vastly overpredicts the breakthrough time, because of the increase of the drainage threshold moisture content ("field capacity") to the level of the effective storage ES. PREFLO provides better results for the breakthrough time, but the results for time to effective storage, discharge and duration of the flow event are erratic, ranging from under- to overpredictions.

CONCLUSIONS

Both water balance and two-domain models can predict leachate generation approximately if key parameters are adjusted. The initial breakthrough time is very short and can be predicted with HELP if the field capacity is set to the practical field capacity value of between 0.1 and 0.12 instead of the default value of 0.292. PREFLO is prone to underpredict breakthrough time due to the drainage from the initial moisture content. The time to effective storage is fairly well predicted by PREFLO and may be predicted by HELP if the "field capacity" is replaced by the value for the effective storage (at about 0.2 to 0.23). Cumulative leachate volume is somewhat erratically predicted by PREFLO and can be moderately well predicted by HELP if the effective storage is set accurately. The duration of the flow events are underpredicted by HELP and overpredicted by PREFLO. There seems to be no reliable parameter modification to achieve accurate prediction of the duration.

While the two-domain approach initially promises some advantages, the specification of key parameters and the routing of infiltration into channels and matrix are difficult. In contrast, HELP cannot accommodate simultaneously both the early discharges from low channels and the moisture redistribution and storage in the matrix. However, HELP with properly modified spatially and temporally averaged parameters of porosity, pore size distribution index, practical field capacity, effective storage, and hydraulic conductivity provides good

Table 4. Comparison of Predicted and Measured Leachate Generation

	Measured Results	Calibrated HELP Prediction		Calibrated PREFLOW Prediction	
Leachate Generation Variables	Experimental Values for Pilot Cells	Predicted Values	Difference to Measured Value as Percent of Measured %	Predicted Values	Difference to Measured Value as Percent of Measured %
High Infiltration Rate—High Density Cells ($n = 2$)					
Breakthrough time t_{bt} [days]	1	1	0	–3 (start before infiltration)	–200
Time to effective storage t_{ES} [days]	6	3	–50	never achieved	n.a.
Cumulative Leachate Volume Q [L]	300	292	–3	244	–19
Duration of Flow Event t_Q [days]	17	15	–12	66	+288
High Infiltration Rate—Low Density Cells ($n = 2$)					
Breakthrough time t_{bt} [days]	1	8	+700	–9	–1,000
Time to effective storage t_{ES} [days]	15	10	–33	effective storage not reached	n.a.
Cumulative Leachate Volume Q [L]	239	164	–31	306	+28
Duration of Flow Event t_Q [days]	17	8	–53	98	+476
Low Infiltration Rate—High Density Cells ($n = 2$)					
Breakthrough time t_{bt} [days]	2	30	+1,400	–3 (start before infiltration)	–200
Time to effective storage t_{ES} [days]	34	31	–9	15	–56
Cumulative Leachate Volume Q [L]	104	95	–9	314	+20
Duration of Flow Event t_Q [days]	57	18	–68	79	+39
Low Infiltration Rate—Low Density Cells ($n = 2$)					
Breakthrough time t_{bt} [days]	2	25	+1,150	3	+50
Time to effective storage t_{ES} [days]	37	26	–30	24	–35
Cumulative Leachate Volume Q [L]	167	138	–17	286	+71
Duration of Flow Event t_Q [days]	47	20	–58	80	+70

estimates of cumulative discharge. Both models are limited by the lack of properly measured parameters that apply specifically to municipal solid waste layers.

A new two-domain leachate prediction approach is called for to reflect channeled and matrix flow based on spatially and temporally averaged bulk waste and flow parameters over the area of one to ten square meter and over time periods of a week to a month.

APPENDIX I

Notation

d	[cm]	Pore diameter
ES	[–]	Effective Storage, moisture content at constant discharge
FC	[–]	Field capacity, as defined in the HELP model, is the moisture content when free drainage ceases on the drainage curve
FCp	[–]	Practical field capacity, the moisture content at which free drainage begins on the wetting curve
h	[m]	Vertical thickness of the waste layer
K_S	$\left[\frac{cm}{s}\right]$	Saturated hydraulic conductivity
K_{us}	$\left[\frac{cm}{s}\right]$	Unsaturated hydraulic conductivity
$K'_{us\text{-}init}$, $K'_{us\text{-}ult}$	$\left[\frac{cm}{s}\right]$	Apparent hydraulic conductivities in the presence of channeling
n	[–]	Porosity
P_c	[cm]	Capillary pressure
q	$\left[\frac{cm}{s}\right]$	Specific discharge

Q	[L]	Cumulative leachate discharge
Re	[–]	Reynolds number
t_{bt}	[min]	Breakthrough time
t_{ES}	[–]	Time to effective storage
λ	[–]	Pore size distribution index
μ	[Pa·s]	Absolute viscosity of the fluid
ρ	$\left[\frac{kg}{m^3}\right]$	Fluid density
θ	[–]	Soil moisture content
θ_r	[–]	Soil moisture content at residual saturation
θ_s	[–]	Soil moisture content at saturation

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