# Predicting and Comparing Infiltration Rates Through Various Landfill Cap Systems Using Water-Balance Models – A Case Study

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## ABSTRACT

Liner systems are important elements which safeguard landfills and other contaminated sites. The main task of surface cover systems is to minimize the infiltration of water into underlying wastes, promoting surface water runoff, evapotranspiration and lateral drainage, and thus reducing leachate production and contaminants mobility. An important aspect of the effectiveness of a surface cover system is its water balance under the climate conditions of a particular site (Berger 2000). In this context, predictive models of the infiltration rate through a landfill cap system can be used as screening tools to support planning and aftercare management of a landfill, in order to estimate the efficacy of a liner system or compare alternative designs and/or optimize particular system with regard to cost-benefit consideration. In this paper, the performances of two water balance models to predict the effective infiltration and leakage rate for different capping systems are discussed. These models are the well-known US EPA HELP Model (Schroeder et al. 1994) and a new simplified screening model called LWB Model (Pantini et al. 2013) that were used for assessing the infiltration rate over a period of 30 years through three different cover options for a US project site in Howard County, Maryland. The obtained results, have shown that both HELP and LWB Models, even though they use different computational approaches, provide very similar values in terms of infiltration rate through the different capping systems. This only confirms that water balance models can be used as a great tool for comparing alternative options to liner systems. However, more effort is still needed to assess the accuracy of these approaches to quantitative predict the infiltration and leakage rates through different cover layers. We believe that the combination of a simplified approach (such as the LWB Model) with a more detailed one (such as the HELP Model) could partially address this problem. In this view, we believe that a simplified LWB Model, which required a limited number of input data, could provide a first screening value of the expected leakage rates that can be used as a starting point in the calibration step of a more detailed model (such as e.g. HELP Model) and also additional insights about the significance and influence of the different input parameters required.

## INTRODUCTION

Liner systems are important elements which safeguard landfills and other contaminated sites limiting contaminant migration to the surrounding environment. The simplest liner consist of either a geomembrane (GM), a compacted clay liner (CCL) or a geosynthetic clay liner (GCL) which involve a thin layer of bentonite clay between two geotextiles. Nowadays, composite liners (CLs), which combine two or more of these components, have become widely used in solid waste and hazardous waste landfills (Foose 2010; Giroud et al. 1992). Alternative configuration for composite liner include, for example, a GM over a CCL, a GM over a GCL or a GM over a GCL over a CCL (Barroso et al. 2006) and can be used in a wide range of applications (Rowe 2012). This paper focuses on their use as landfill cover systems. The main task of a surface cover system is to minimize the infiltration of rain water into wastes, promoting surface water runoff, evapotranspiration and lateral drainage, and thus reducing leachate production and contaminants mobility.

To ensure isolation of waste body against surface water infiltration, different type of capping systems can be realized, which may vary from a simple soil cover to a multiple-barrier layers of natural and geosynthetic materials (Kampf & Montenegro 1997), depending on the standard regulatory requirements.

The design of a landfill liner system can be made either on a prescriptive basis, which follows the requirements specified by regulations, or on a performance basis, which implies a modeling of advective and diffusive flow through liners in order to evaluate percolation over time (Touze-Foltze et al. 2008). A performance-based analysis is more complex than the former, since it requires to take into account for numerous parameters and for the service life of each component of the liner (i.e. GM deterioration or cracking of soil). For instance, leakage through a composite liners including a GM is mainly due to the advective flow through geomembrane holes, since this component is essentially impervious to water diffusion (Katsumi et al. 2001, Foose 2010, Rowe 2012). Defects, which can occur during manufacturing, transportation, handling and installation of GM sheets, represent preferential pathways for water flow and their occurrence may vary in a wide range, from a minimum of 2.5-5 defects/ha (good quality control) to a maximum of 17-22 defects/ha (poor assurance), as observed by several authors (Forget et al. 2005, Giroud & Bonaparte 1989, Katsumi et al. 2001, Nosko & Touze-Foltz 2000).

In last decades, several experimental studies were carried out in order to quantify flow rates through composite liner (Barroso et al. 2006, Cartaud et al. 2005, Chai & Miura 2002, El-Zein 2012, Foose 2010, Saidi et al. 2008), by using different approaches (i.e. analytical or numerical models and lab or field tests). In this context, predictive models of the infiltration rate through a landfill cap system can be used as screening tools to support planning and aftercare management of a landfill, in order to estimate the efficacy of a liner system or compare alternative designs and/or optimize particular system with regard to cost-benefit consideration.

In this paper, the performances of two water balance models to predict the effective infiltration and leakage rates for different capping systems are discussed. These two models are the well-known US EPA HELP Model (Schroeder et al. 1994) and a new simplified screening model called LWB Model (Pantini et al. 2013) that were used for assessing the infiltration rate over a period of 30 years through three different cover options for a US project site in Howard County, Maryland.

## Fundamental of Seepage Through CLs in HELP and LWB Models

In order to evaluate and compare different type of cover systems, the HELP and LWB models apply the following water balance equation to the considered layers:

$$L(t_i) = \left[P(t_i) - R(t_i) - ET_r(t_i) \pm \Delta U(t_i)\right] \cdot A \qquad \text{(eq. 1)}$$

Where L is the leakage through the liner ($L^3$), P is the rainfall (L), R is the superficial runoff (L), $ET_r$ is the actual evapotranspiration (L), $\Delta U$ is the change in soil water storage (L) , A is the surface area ($L^2$) and $t_i$ is the time step of calculation.

*Runoff*. In both models, runoff is computed using the SCS-Curve Number method (USDA, Soil Conservation Service 1985) adjusted for slope and soil moisture condition. Specifically, HELP model accounts for the degree of saturation of the topsoil, whereas LWB model always assumes initial dry conditions for surface layer following a conservative and simplified approach.

*Evapotranspiration*. Regarding the actual evapotranspiration, in both models it is computed comparing the potential evapotranspiration with the total amount of water available for this process, i.e. the water stored within the evaporative zone depth. In the HELP Model, potential evapotranspiration is modeled by a modified Penman's method, which is an energy-based model, accounting for net radiation, wind speed, vapor pressure, humidity and air mean temperature on daily basis. In the LWB Model, the well-known Thornthwaite (1948) method (temperature-based model), which accounts for monthly air temperature and average number of daylight hours (depending on local latitude), is implemented. In addition, the LWB Model accounts for vegetation cover type through a crop coefficient $K_c$ which considers both crop characteristics and seasonal variation of plant activity (i.e. for a turf grass $K_c$ varies from 0.95 in cool season to 0.85 in warm season, Allen et al. 1998). Recharge of soil water storage is evaluated based on daily distribution of rainfall. More specifically, in the LWB Model the water available for evapotranspiration is calculated accounting for equivalent rainy days (computed as the ratio of the monthly precipitation and the water storage capacity of surface layer) and for soil characteristics (field capacity, wilting point and thickness).

*Leakage, Lateral Drainage and Change in water storage*. In both models, the change in water storage is computed considering soil retention capacity and net lateral drainage between layers.

Leakage through a composite liners including a GM is mainly due to the advective flow through geomembrane holes, since this component is essentially impervious to water diffusion (Katsumi et al. 2001, Foose 2010). Defects, which can occur during manufacturing, transportation, handling and installation of GM sheets, represent preferential pathways for water flow and their occurrence may vary in a wide range, from a minimum of 2.5-5 defects/ha (good manufacturing quality control) to a maximum of 17-22 defects/ha (poor installation quality), as observed by several authors (Forget et al. 2005, Giroud & Bonaparte 1989, Katsumi et al. 2001,Nosko & Touze-Foltz 2000). In last decades, several experimental studies were carried out in order to quantify flow rates through composite liner (Barroso et al. 2006, Cartaud et al. 2005, Chai & Miura 2002, El-Zein 2012, Foose 2010, Saidi et al. 2008), by using different approaches (i.e. analytical or numerical models and lab or field tests).

In the HELP Model, leakage through GM is computed to be the result of three sources: vapor diffusion, manufacturing flaws (pinholes) and installation defects. Vapor diffusion through intact GM is computed as function of the head on the surface of the liner, the thickness of the GM and its vapor diffusivity. Leakage rates through defects and pinholes in GM are computed by applying empirical formulations proposed by Giroud & Bonaparte 1989, depending on the quality of contact between the GM and the soil below. The basic equation for estimating leakage through circular flaws in geomembranes with interfacial flow is the following (Schroeder et al. 1994):

$$q_L = K_s \cdot i_{avg} \cdot \eta \cdot \pi R^2 \left( \frac{\eta_{20}}{\eta_{15}} \right) \qquad \text{(eq.2)}$$

Where $q_L$ is the leakage rate through pinholes or defects with interfacial flow, Ks is the saturated hydraulic conductivity of controlling soil layer, $i_{avg}$ is the average hydraulic gradient on the wetted area of controlling soil layer from pinholes or defects (dimensionless), $\eta$ is the density of pinholes or defects, R is the radius of wetted area or interfacial flow around a pinhole or an installation defect, $\eta_{20}$ and $\eta_{15}$ are the absolute water viscosity at 20°C (0.001 kg/ms) and at 15°C (0.00114 kg/ms), respectively. The HELP Model also applies the following equation for assessing the average hydraulic gradient:

$$i_{avg} = 1 + \left[ \frac{h_g}{2T_s \ln\left( \frac{R}{r_0} \right)} \right] \qquad \text{(eq.3)}$$

Where $h_g$ is the average hydraulic head on the liner, $T_s$ is the thickness of soil layer at base, $r_0$ is the radius of flaw (HELP assigns for pinhole $r_0$ = 1mm and for defect $r_0$= 6 mm)

The radius of wetted area is computed using equation proposed by Giroud & Bonaparte 1989, according to the type of flaw (pinhole or defect) and to the quality of contact (excellent, good, poor):

$$\text{Good liner contact} \begin{cases} R = 0.174 \cdot h_g^{0.45} \cdot K_s^{-0.13} & \text{pinholes} \\ R = 0.222 \cdot h_g^{0.45} \cdot K_s^{-0.13} & \text{defects} \end{cases} \qquad \text{(eq.4)}$$

$$\text{Poor liner contact} \begin{cases} R = 0.174 \cdot h_g^{0.45} \cdot K_s^{-0.13} & \text{pinholes} \\ R = 0.521 \cdot h_g^{0.45} \cdot K_s^{-0.13} & \text{defects} \end{cases} \qquad \text{(eq.5)}$$

The radius (eqs. 4,5) and the average hydraulic gradient (eq.3) are then used in eq.2 to compute the leakage rate for geomembranes flaws. These equations are valid for saturated hydraulic conductivity of the controlling soil layer less than $10^{-4}$ cm/s.

Good contact minimizes leakage, since a smaller area of the soil liner is exposed to the flow, and corresponds to a GM installed on top of the low-permeability soil layer that has been adequately compacted and has a smooth surface (Giroud et al. 2002). Whereas poor contact permits greater leakage because liquid can freely penetrate at the interface between the GM and the underlying soil; this condition corresponds to a

GM that has been installed with a certain number of wrinkles and/or placed on a low-permeability soil layer that has not been adequately compacted and does not appear smooth (Giroud et al. 2002).
In the absence of GM, the leakage through the clay liner ($L_C$) during the time step $t_i$ is calculated using the Darcy's law, knowing the hydraulic conductivity of clay ($K_C$), the water head ($\Delta H$) and the thickness of clay liner ($s_C$):

$$L_C(t_i) = K_C \cdot \frac{\Delta H + s_C}{s_C} \cdot A \qquad \text{(eq.6)}$$

In the LWB Model, it uses a simplified method assuming that the liquid flow in the capping layers is bound by the lower permeable layer, which may be the clay layer or the geosynthetic (GM).
More specifically, for composite liner with the GM, leakage is computed considering both diffusive flux through geosynthetic material and the advective flow through the holes. Under this assumption, the water head on the top of lower permeable material is computed using the following equation (Pantini et al. 2013):

$$\Delta H(t_i) = \frac{-\left(\frac{K_x}{s_x} \cdot A_x + \xi\right) + \sqrt{\left(\frac{K_x}{s_x} A_x + \xi\right)^2 + 2 \cdot B \cdot \frac{K_d}{D_c} \cdot \left(I_{ef}(t_i) \cdot A + Q_{lat}(t_i) - K_x \cdot A_x\right)}}{B \cdot \frac{K_d}{D_c}} \qquad \text{(eq.7)}$$

$$\begin{cases} \xi = 0; \quad K_x = K_c; \quad s_x = s_c & \text{no synthetic layer} \\ \xi = K_s \cdot \eta \cdot A_g / s_g; \quad K_x = K_g; \quad s_x = s_g & \text{synthetic layer} \end{cases} \qquad \text{(eq.8)}$$

with the subscript $x$ referring to either the geomembrane (g) or of the low-permeability soil layer (c).

$K_x$ is the hydraulic conductivity of the layer $x$, $s_x$ the thickness of the layer $x$, $A_x$ the area of the layer $x$, $K_d$ the hydraulic conductivity of drainage layer, $I_{ef}$ the effective infiltration (i.e. $I_{ef} = P - R - ET_r$), $Q_{lat}$ the net lateral flow, $D_c$ the distance to the water collection system and B the cell-size along orthogonal direction to the main direction of flow. It is worth noting that in the simplified LWB model approach, the only "fitting" parameter is the percentage of cracking, $\eta$, which determines the total defect area.
Lateral water flow ($Q_D$) that moves away without infiltrating in the layer, is computed through Darcy's equation as a function of the hydraulic conductivity of drainage layer ($K_d$) and the water head ($\Delta H$):

$$Q_D(t_i) = K_d \cdot \frac{B}{D_c} \cdot \frac{\Delta H^2(t_i)}{2} \qquad \text{(eq. 9)}$$

Finally, the leakage through geomembrane liner is calculated as:

$$L(t_i) = K_g \cdot A_g(t_i) \cdot \frac{\Delta H(t_i) + s_g}{s_g} + K_s \cdot \eta \cdot A_g(t_i) \cdot \frac{\Delta H(t_i)}{s_g} \qquad \text{(eq. 10)}$$

For clay liner systems leakage is computed through eq. 6, once the hydraulic head has been evaluated from eqs. 7 and 8.

## MATERIALS AND METHODS: THE CASE STUDY

In this case study, the HELP and the LWB Models were used for assessing the infiltration rate and leakage through three different capping options presented in Figure 1. The project site is in Howard County, Maryland, where two cap systems were eventually installed; the soil cap on the plateau area and the geomembrane on the side slope. The different alternatives considered are displayed below.

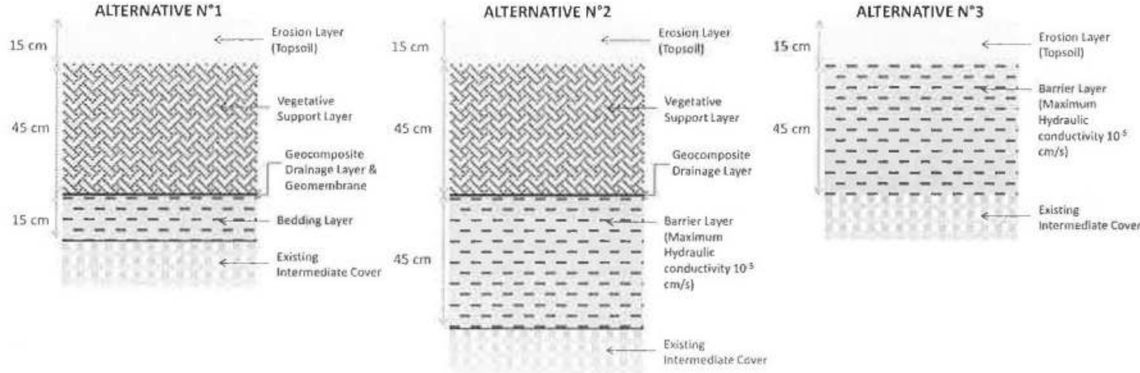


**Figure 1 Alternative capping systems assumed for simulations with HELP and LWB models.**

### Alternative N°1

Capping system in Alternative N°1 is composed by the following layer (from top to bottom):

1. Erosion layer of moderately compacted loam: thickness 15 cm, porosity $41.9\%_{v/v}$, field capacity $30.7\%_{v/v}$, wilting point $18\%_{v/v}$, initial water content 27.16 $\%_{v/v}$, saturated hydraulic conductivity of $1.9\ 10^{-5}$ cm/s.
2. Vegetative support layer of silty clay loam: thickness 45 cm, porosity $47.1\%_{v/v}$, field capacity $34.2\%_{v/v}$, wilting point $21\%_{v/v}$, initial water content 38.45 $\%_{v/v}$, saturated hydraulic conductivity of $4.2\ 10^{-5}$ cm/s.
3. Geocomposite liner composed of a geocomposite drainage layer (hydraulic conductivity of 5 cm/s) over a LLDPE geomembrane (permeability of $4\ 10^{-13}$ cm/s, pinhole density of 2/ha , defect density of 5/ha, good placement quality, $\eta$ of $4\ 10^{-6}$ %) and a bedding layer of compacted soil.
4. Support layer of silty clay loam: thickness 15 cm, porosity $47.1\%_{v/v}$, field capacity 34.2 $\%_{v/v}$, wilting point $21\%_{v/v}$, initial water content 37.51 $\%_{v/v}$, saturated hydraulic conductivity of $4.2\ 10^{-5}$ cm/s.

### Alternative N°2

Capping system in Alternative N°2 is composed by the following layer (from top to bottom):

1. Erosion layer of moderately compacted loam: thickness 15 cm, porosity $41.9\%_{v/v}$, field capacity $30.7\%_{v/v}$, wilting point $18\%_{v/v}$, initial water content 30 $\%_{v/v}$, saturated hydraulic conductivity of $1.9\ 10^{-5}$ cm/s.
2. Vegetative support layer of silty clay loam with the same characteristics of alternative 1.
3. Geocomposite drainage layer (hydraulic conductivity of 5 cm/s) over a soil barrier liner (hydraulic conductivity of $10^{-5}$ cm/s)
4. Support layer of silty clay loam: thickness 15 cm, porosity $47.1\%_{v/v}$, field capacity 34.2 $\%_{v/v}$, wilting point $21\%_{v/v}$, initial water content 40.26 $\%_{v/v}$, saturated hydraulic conductivity of $4.2\ 10^{-5}$ cm/s.

### Alternative N°3

Capping system in Alternative N° 3 is composed by the following layer (from top to bottom):

1. Erosion layer of moderately compacted loam: thickness 15 cm, porosity $41.9\%_{v/v}$, field capacity 30.7 $\%_{v/v}$, wilting point $18\%_{v/v}$, initial water content 27.16 $\%_{v/v}$, saturated hydraulic conductivity of $1.9\ 10^{-5}$ cm/s.
2. Soil barrier liner of compacted clay: thickness 45 cm, porosity $42.7\%_{v/v}$, field capacity 41.8 $\%_{v/v}$, wilting point $36.7\%_{v/v}$, initial water content 42.7 $\%_{v/v}$, saturated hydraulic conductivity of $10^{-5}$ cm/s.
3. Support layer of silty clay loam: thickness 15 cm, porosity $47.1\%_{v/v}$, field capacity 34.2 $\%_{v/v}$, wilting point $21\%_{v/v}$, initial water content 37.51 $\%_{v/v}$, saturated hydraulic conductivity of $4.2\ 10^{-5}$ cm/s.

For all the alternatives, a total area of 1 hectare was assumed.

Moreover, in order to evaluate the effect of clay conductivity on the performance of different capping alternatives, other simulations were conducted changing the permeability of clay from $10^{-5}$ cm/s to $10^{-7}$ cm/s. For the different simulations, weather data were generated for a thirty-year period using the HELP synthetic generator program WGEN and inserting the latitude of the site (39°18' N). Table 1 shows average monthly values of rainfall and air temperature for the considered site; these values are averaged over a period of thirty years. However, it should be noted that weather daily values were used for the simulations carried out with both models and reported in the following section.

**Table 1 Average monthly values of rainfall and of air temperature used in HELP and LWB simulations.**

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rainfall (mm) | 76.2 | 75.7 | 94.5 | 85.1 | 87.4 | 95.5 | 98.8 | 117.3 | 87.9 | 79.0 | 79.0 | 86.4 |
| Temperature (°C) | 0.4 | 1.5 | 6.3 | 12.2 | 17.5 | 22.4 | 24.9 | 24.2 | 20.5 | 13.8 | 8.0 | 2.5 |

Finally, runoff was estimated using a SCS curve number (CN) of CN=90.4 in HELP and of CN=89 in the LWB model.

## RESULTS AND DISCUSSION

In this section, simulation results provided by the two models for this case study are presented and compared. A summary of the average simulation results for the different alternative capping systems obtained applying HELP and LWB model is reported in Table 2. Values of runoff, evapotranspiration, effective infiltration, leakage and lateral drainage are expressed as average values over the thirty-year period of simulations.

**Table 2 Comparison of averaged values of runoff (R), actual evapotranspiration ($ET_r$), effective infiltration ($I_{ef}$), leakage (L) and lateral drainage ($Q_D$) simulated by the HELP and the LWB models for the different alternative cap systems. Average annual precipitation (P) is also reported.**

| | P (mm/yr) | R (mm/yr) | | $ET_r$ (mm/yr) | | $I_{ef}$ ($m^3$/ha/yr) | | L ($m^3$/ha/yr) | | $Q_D$ ($m^3$/ha/yr) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | HELP | LWB | HELP | LWB | HELP | LWB | HELP | LWB | HELP | LWB |
| Alternative N °1 | 1 051 | 178 | 225 | 737 | 645 | 1 355 | 1 797 | 0,06 | 0,09 | 1 357 | 1 797 |
| Alternative N°2 , $K=10^{-5}$ cm/s | | 178 | 225 | 737 | 645 | 1 355 | 1 797 | 1 095 | 1 779 | 262 | 18 |
| Alternative N°2 , $K=10^{-7}$ cm/s | | 178 | 225 | 737 | 645 | 1 355 | 1 797 | 83 | 48 | 1 274 | 1 749 |
| Alternative N°3 , $K=10^{-5}$ cm/s | | 194 | 225 | 590 | 578 | 2 663 | 2 473 | 2 663 | 2 466 | --- | --- |

Figure 2 reports the annual trends of leakage through the GM in Alternative N° 1 using the HELP (purple) and the LWB (green) models. One order of magnitude of the reduction in water flow was estimated due to the presence of a geomembrane liner. Annual values of effective infiltrations predicted with the two models are also reported. It can be noticed that, in both models, the leakage through GM is about 0.005-0.01 % of effective infiltration, even though the net infiltrations predicted with the LWB model are averagely 1.4 times greater than those provided by HELP. This is probably due, on the one hand, to the lower evapotranspiration rate obtained with the Thornthwaite's method (1948) with respect to Penman's method (1963) and, on the other hand, to the differences in modeling leakage through geomembrane's holes.

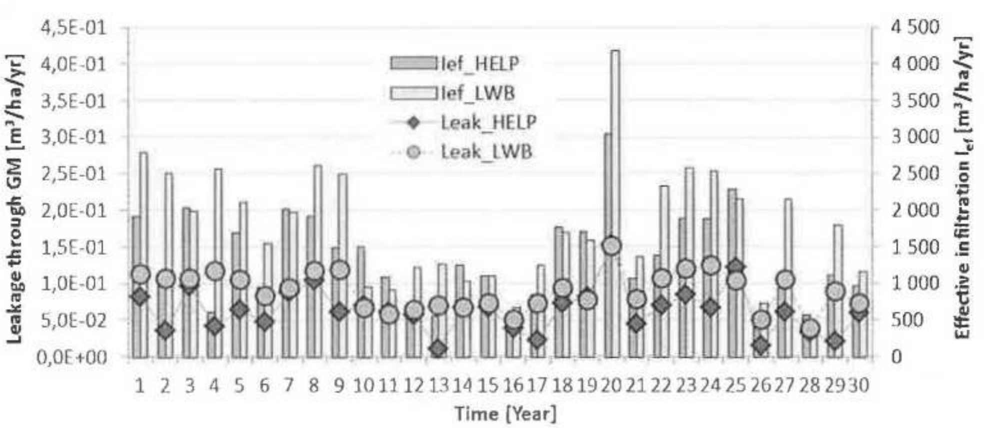


**Figure 2 Annual trend of effective infiltration (bars) and leakage through GM (symbols) provided by the HELP and LWB models for the capping system N°1.**

Results of Alternative N°2 are presented in Figure 3, which refers to the conditions of a clay hydraulic conductivity ($K_{clay}$) of $10^{-5}$ cm/s (Figure 3a) and of $10^{-7}$ cm/s (Figure 3b), respectively. According to the results provided by the LWB model, this capping configuration, using a $K_{clay}$ of $10^{-5}$ cm/s, ensures a slight reduction of water infiltration; in fact, leakage through the bottom layer corresponds to 97-100 % of the effective infiltration and lateral drainage occurs only in a few years and with low flows. On the contrary, reducing the clay conductivity to $10^{-7}$ cm/s (Figure 3 b), the LWB model estimates very low leakage rate, about 1-8 % of the net infiltration, promoting water removal in the drainage layer (average value of 1.8 $10^3$ $m^3$/ha/year ). A similar trend is also obtained with the HELP model. Even though percolation rates through the bottom liner in HELP are higher than those of LWB, HELP results suggest that decreasing the clay hydraulic conductivity by two orders of magnitude, from $10^{-5}$ to $10^{-7}$ cm/s, reduce leakage rates to about 92% (vs 97% obtained with the LWB model).

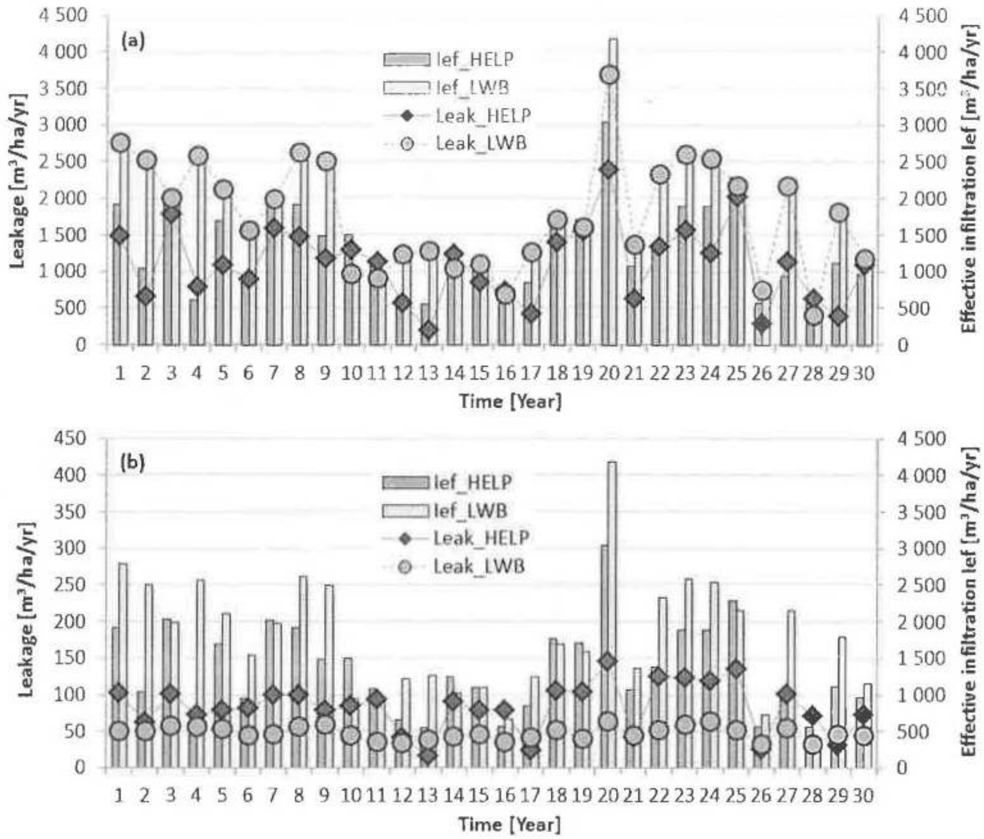


**Figure 3 Annual trend of effective infiltration (bars) and leakage through GM (symbols) provided by HELP and LWB models for the capping system N°2, assuming the hydraulic conductivity of clay of $10^{-5}$ cm/s (a) and $10^{-7}$ cm/s (b), respectively.**

Finally, simulation results of Alternative N°3 ($K_{clay}$ of $10^{-5}$ cm/s) are reported in Figure 4. As expected, this capping configuration produces the worst performance for limiting water infiltration. In fact, according to both models' predictions, nearly all the amount of water infiltration overcome this barrier and therefore enters the landfill body. Moreover, the ability of the superficial soil to act as a water reservoir enhancing evapotranspiration is more restricted comparing to Alternatives N° 1 and N°2. In fact, in capping Alternative N°3 the lower thickness of surface soil (by 45 cm) over the soil barrier liner corresponds to a lower water holding capacity and leads to a minor evapotranspiration losses and thus greater infiltration rates.

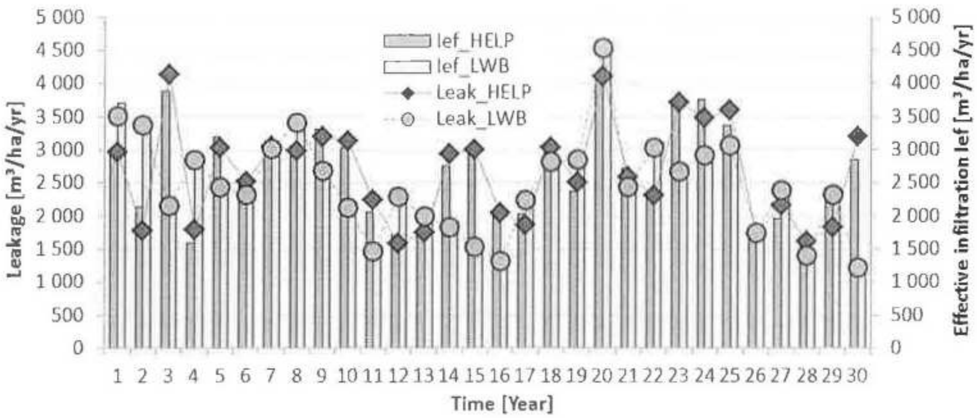


**Figure 4 Annual trend of effective infiltration (bars) and leakage through GM (symbols) provided by the HELP and LWB models for the capping system N°3, assuming the hydraulic conductivity of clay of $10^{-5}$ cm/s.**

It can be noticed that HELP and LWB models provided very similar values, even though they use different computational approaches. The best performance in reducing infiltration rates is performed by the Alternative N°1 and the worst by the Alternative N°3 (soil only). In fact, the results indicate that leakage through GM in Alternative N°1 is a very small fraction of water budget (from 0.0005 % to 0.0012% of annual rainfall for the LWB and from 0.0001 % to 0.0012 % for HELP) whereas lateral drainage contributes greatly (from 5% to 33% of precipitations for LWB and from 2% to 25% for HELP). Both in HELP and LWB simulations, surface runoff has a quite influence on water budget, accounting for 8-30 % in HELP and 11-30% in LWB, whereas evapotranspiration comprises the largest fraction, 60-83 % in HELP and 49-83% in LWB; these data are in line with other researches (Vlyssides et al. 2003, Albright et al. 2004).

One of the major differences between the two models is related to the Alternative N°2 with the hydraulic conductivity of clay of $10^{-5}$ cm/s.

In the LWB Model, this value of hydraulic conductivity seems not to prevent the infiltration of water into underlying layers and thus lateral drainage occurs very rarely with low values (leakage ranges from 5% to 30% of annual rainfall and lateral drainage from 0% to 3%). On the contrary, in HELP simulations lateral drainage is one order of magnitude greater (0.3%-6% of annual rainfall). Furthermore, the hydraulic conductivity of the soil barrier liner may allow to attenuate percolation up to one order of magnitude in both models (from 1779 to 48 m$^3$/ha/yr in LWB and from 1095 to 83 in HELP m$^3$/ha/yr). In fact, leakage through the bottom layer contributes only for 0.2-1.2% of annual rainfall in HELP and for 0.4-0.6% in LWB whereas the major contribution of water budget (together with the evapotranspiration) becomes the lateral drainage (2-24% in HELP and 12-40% in LWB).

Generally, LWB model predicted higher values of effective infiltration compared with HELP mainly due to lower evapotranspiration losses and also possibly use of Darcy's Law. Moreover, it can be observed that the two models provide quite different values of surface runoff which is probably due to a different implementation of the SCS curve number method within the two models. Surface runoff computed in LWB seems not to be affected by the type of cover since it essentially depends on the characteristics of the surface soil layer which is the same in all the alternatives whereas in HELP simulations slightly difference of runoff values between alternative N°3 and alternatives N°1, 2 can be found.

## CONCLUSIONS AND FINDINGS

The ability to evaluate the long-term hydrological performance of a liner system is valuable both when designing stormwater and leachate collection and treatment systems and estimating the construction and operating costs of a landfill. To this end, predictive models of leakage through composite liners represent useful tools. In this paper, two water-balance models, HELP and LWB, were applied to assess the leakage rate through three cover systems (a GM liner cap, a composite liner cap and a soil barrier cap).

The results obtained from both models showed that, as expected, conventional covers with soil barriers only (Alternative N°3) are not effective for limiting water infiltration whereas the best protective action is guarantee by a composite liner system with a geomembrane (Alternative N°1), even though much depends

on its integrity and on the quality of contact with the soil below. Moreover, results of both model simulations showed that, to ensure the protective action of a composite liners cap CLs (Alternative N°2), a key aspect is represented by the hydraulic conductivity of the clay layer. For a higher hydraulic conductivity ($10^{-5}$ cm/s) value, the performance of CLs are very poor and are comparable to those of a soil barrier. However, when adopting a lower value of clay hydraulic conductivity ($10^{-7}$ cm/s), the performance of CLs appear successful, with leakage close to those of geomembrane liners. In addition, the results suggest that the effectiveness of a cover system could be also strongly affected by the water storage capacity of the surface soil layer and by the type of vegetation cover which have a great influence on evapotranspiration and surface runoff losses.
Finally, the results reported in this paper, showed that the two models, even though based on very different approaches, provide, in nearly all cases, very similar predictions of the expected leakage rates. However, these results only confirm that water balance models could be great tools for comparing alternative options for liner systems but do not provide indications about the accuracy of these approaches to estimate the infiltration rates through the different cover layers. In fact, it is well known, that in some cases results obtained from water balance models fail to compare to the actual field data collected. As reported by different authors in literature, this could be due to, on the one hand, the basic assumptions of the models, and, on the other hand, the large amounts of input data (some of them hardly identifiable from the field data generally available) required for their application. We believe that the combination of a simplified approach (such as the LWB) with a more detailed one (such as HELP) could partially address this problem. Therefore, we believe that a simplified LWB Model, which requires a limited number of input data, could provide a first screening value of the expected leakage rates that can be used as a starting point in the calibration step of a more detailed model (such as e.g. HELP Model) and additional insights about the significance and influence of the different input parameters required.

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