An attempt to perform water balance in a Brazilian municipal solid waste landfill

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ABSTRACT

This paper presents an attempt to model the water balance in the metropolitan center landfill (MCL) in Salvador, Brazil. Aspects such as the municipal solid waste (MSW) initial water content, mass loss due to decomposition, MSW liquid expelling due to compression and those related to weather conditions, such as the amount of rainfall and evaporation are considered. Superficial flow and infiltration were modeled considering the waste and the hydraulic characteristics (permeability and soil–water retention curves) of the cover layer and simplified uni-dimensional empirical models. In order to validate the modeling procedure, data from one cell at the landfill were used. Monthly waste entry, volume of collected leachate and leachate level inside the cell were monitored. Water balance equations and the compressibility of the MSW were used to calculate the amount of leachate stored in the cell and the corresponding leachate level. Measured and calculated values of the leachate level inside the cell were similar and the model was able to capture the main trends of the water balance behavior during the cell operational period.

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1. Introduction

The water balance is a fundamental tool for landfill design and management. The volume of collected leachate is a key parameter in the design of the leachate treatment and drainage facilities and the volume of water stored in the waste mass may play an important role in the stability issues of the landfill. A water balance basically consists of the calculation of the input and output of liquids in the landfill system. Despite the simplicity of the definition, the water balance must take into account a number of variables that can be difficult to evaluate in the field. Climatic aspects, such as the amount of rainfall and evaporation, hydraulic and mechanical properties of MSW and soil cover, as well as specific aspects of the landfill management must be considered in the water balance.

The water inputs and outputs normally considered in landfill water balance include the changes in water with the atmosphere (rain, condensation, sublimation, evaporation and evapotranspiration), superficial flow, infiltration, the MSW and the soil cover water contents and the volume of collected leachate. Using the mass conservation principle, the amount of water stored in the system can be calculated by integrating the differences between the

input and output flow rates over time. Table 1 lists some papers which discuss the water balance in Brazil and in other countries around the world. Analyzing the adopted approaches to performing a water balance in these papers it can be said that:

- The water consumed by the MSW biodegradation processes is not considered in the water balance.
- The cover material and the MSW geotechnical properties such as permeability, porosity and compressibility are not clearly presented in the water balances.
- The loss of water in the form of vapor during biogas extraction is not considered. According to Blight et al. (1997) this output can be neglected.
- MSW water expelling due to compression is not explicitly considered in the water balance.
- The stored water/leachate in the system is considered as a whole without distinguishing between free water and the water bonded to the MSW solid particles.

Still considering the papers listed in Table 1, it may be said that Blight et al. (1997) and Blight and Fourie's (1999) papers better describe and detail the water balance components.

Regarding the programs designed to perform landfill water balance, HELP – hydrologic evaluation of landfill performance (Schroeder et al., 1994) is the most well-known worldwide and versions 2 and 3 of the software MODUELO (MODUELO, 2006) are the most complete options for water balance modeling. They simultaneously consider water and solid balances and the water

Abbreviations: HELP, hydrologic evaluation of landfill performance; MCL, metropolitan center landfill; MSW, municipal solid waste.

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Nomenclature

$(\partial I_{(\text{soil})}/\partial t)$	infiltration capacity of the soil (L/T)	VS	volatile solids (–)
$(\partial \text{RA}/\partial t)$	rain intensity (L/T)	$V_{w \text{ biodeg}}$	volume of water consumed in the biodegradation process (L^3)
A_k	adjusted soil permeability (L/T)	$V_{w \text{ decomp}}$	volume of liquid that becomes free to flow as a result of MSW degradation (L^3)
A	ratio between the overall compressibility of the waste and the average compressibility of waste particles	$V_{w \text{ vapor}}$	volume of water extracted from landfill with biogas (L^3)
$A_{(\text{MSW})}$	landfill cell cross-section (L^2)	$Z_{(\text{MSW})}$	total thickness of the MSW in the cell (L)
C_m	methane generation per MSW dry mass of effectively degraded material (L^3/M)	α	fitting parameter of soil retention curve (L^{-1})
E	evaporation (L)	γ_s	specific unit weight of the MSW solid particles (F/L^3)
e	void ratio (–)	Δw	change in the gravimetric water content of the MSW (–)
e_o	initial void ratio (–)	θ_o	initial volumetric water content of the soil (–)
E_p	evaporation rate in water or potential evaporation (L)	λ	MSW compression index (–)
h_o	suction head (negative pressure head) at the initial water content of the soil (L)	ρ_d	dry density of the soil cover layer (F/L^3)
h_{surf}	water head above the soil surface (L)	$\rho_{d\text{max}}$	maximum dry density of the soil cover layer (F/L^3)
$I_{(\text{MSW})}$	water infiltration in the MSW (L)	ρ_s	specific unit weight (F/L^3)
$I_{(\text{soil})}$	water infiltration in the soil cover layer (L)	σ	total stress at the average height of the water table (F/L^2)
k	constant related to the biodegradation rate (–)	σ'	effective stress at the average height of the water table (F/L^2)
k_{sat}	soil permeability (L/T)	σ_z	effective vertical stress (F/L^2)
L	volume of collected leachate (L^3)	$\Delta z_{(\text{MSW})}$	thickness of each disposed layer of MSW in the cell (L)
m_v	fitting parameter of soil retention curve (–)	$\Delta z_{(\text{soil})}$	cover layer thickness (L)
n_m	number of moles of water vapor that leaves the landfill (mol)	$\Delta \theta$	changes in the volume of stored water in the system (–)
n	soil porosity (–)	$\Delta \theta_{(\text{soil})}$	change in the volumetric water content of the soil cover (–)
N	MSW specific volume (–)	$\Delta \theta_{\text{comp}(\text{MSW})}$	volumetric water content variation due to MSW compression and water expelling (–)
n_v	fitting parameter of soil retention curve (–)	$\theta_{(\text{free})}$	free liquid (–)
P_v	water vapor pressure for a given temperature ($\text{M T}^{-2} \text{L}^{-1}$)	$\theta_{(\text{MSW})}$	MSW average volumetric liquid content (–)
RA	amount of rain (L)	$\theta_{\text{ads}(\text{MSW})}$	liquid associated or bonded to the MSW (–)
R	gas universal constant ($8.314 \text{ M T}^{-2} \text{L}^2/\text{mol K}$)	$\theta_{\text{cc}(\text{soil})}$	soil–water content at field capacity (–)
RO	runoff or superficial flow (L)	θ_f	final volumetric water content of soil (–)
S	water absorption capacity of the soil ($\text{L T}^{-1/2}$)	$\theta_{i(\text{MSW})}$	initial volumetric water content of the MSW (–)
S_r	average saturation degree of the MSW (–)	$\theta_{i(\text{soil})}$	initial volumetric water content of the soil cover (–)
t	elapsed time (T)	θ_r	soil residual volumetric water content (–)
T	biogas temperature (K)	θ_{sat}	saturated volumetric water content (–)
u_w	water pore pressure at the average height of the water table (F/L^2)		
V	volume of extracted biogas (L^3)		
$V_{(\text{MSW})}$	MSW overall volume (L^3)		

Table 1

Water balance research into municipal solid waste (MSW). Some papers dealing with water balance in MSW landfills.

Author and year	Country
Blight and Fourie (1999)	South Africa
Capelo Neto et al. (1999)	Brazil
Monteiro et al. (2001)	Brazil
Dwyer (2001)	USA
Gomes et al. (2002)	Brazil
Pessin et al. (2002)	Brazil
Medeiros et al. (2002)	Brazil
Lange et al. (2002)	Brazil
Cortázar et al. (2003)	Spain
Visvanathan et al. (2003)	Thailand
Marques and Manzano (2003)	Brazil
Fellner et al. (2003)	Austria
Gisbert et al. (2003)	France
Blight et al. (2003)	South Africa
Albright et al. (2003)	USA
Hadj-hamou and Kavazanjian (2003)	USA
Marques and Vilar (2003)	Brazil
Simões et al. (2003)	Brazil
Padilla et al. (2007)	Brazil
Coelho et al. (2007)	Brazil
Catapreta (2008)	Brazil

balance includes the cover layer balance and water percolation into the waste mass.

However, some research carried out in recent years (Marques and Vilar, 2003; Padilla et al., 2007, among others) and local practice have shown that in tropical countries while the landfill cover has an important influence on the reduction in the volume of leachate, the amount of water that enters the landfill with the MSW and its posterior expelling by waste compression must be considered in the landfill water balance. Marques and Vilar (2003) evaluated the effects of waste compaction on leachate generation at an experimental landfill at Bandeirantes Landfill, São Paulo, Brazil. The authors showed that the volume of collected leachate was always higher than the values obtained using HELP. Schueler (2005) applied HELP to perform water balances in the Paracambi landfill, Rio de Janeiro. Again, the volume of leachate generated was higher than that obtained using HELP. The author cites the fact that HELP does not consider leachate released from solid waste biodegradation reactions, one of the reasons for the observed discrepancies.

Padilla et al. (2007), using MODUELO, obtained accumulated leachate production 20–30% lower than field measurements in an experimental cell in the Central of Solid Waste Treatment, Belo Horizonte, Brazil. The results showed that the initial water content

of the MSW had more influence on the calculation of leachate production than field capacity (the amount of water content held in porous media after excess water has drained away and the rate of downward movement has materially ceased) and preferential percolation paths. MODUELO was also applied to one of the landfill cells and the calculated volume of leachate was about 44% of the measured values. The author attributed most of the observed differences to the fact that the initial water content of the MSW was not included in the simulations due to field experimental problems. Generally, Brazilian experiences have shown that the use of water balance models tends to underestimate leachate generation and some of the reasons for this are examined in this paper.

Machado et al. (2009) reported MSW water content values of around 92% (dry basis) for fresh (new) waste that enters the metropolitan center landfill (MCL) Salvador, Brazil. According to these authors, this amount increases on rainy days due to temporary waste storage in backyards of houses or on the streets. Confined compression tests, carried out in the laboratory (São Mateus, 2008) using the same waste, have shown that most of the MSW water content becomes free water under compression. When the amount of expelled water is compared to the volume of collected leachate, the results suggest that this factor is one of the main contributors to leachate generation in the landfill.

The water balance must consider the contribution of the biodegradation processes on leachate generation. Some of the organic compounds of MSW have an excess of water compared to the amount of water necessary for biodegradation. This excess of water is released by the decomposed material and contributes to the amount of water stored in the cell.

The height of the landfill influences the water balance as the greater the thickness of the waste body, the higher the waste compression and the amount of water expelled from the solid particles. As well as this, waste compression reduces void ratio and therefore the leachate level inside the cell rises, even without variation in the volume of free water stored in the cell.

Most of the proposed models do not consider these aspects in the water balance. Although some of them distinguish water attached to waste particles from free water (leachate), many of the related aspects are neglected, leading to poor performance in many situations.

This paper presents a simplified procedure to perform a water balance in landfill cells. The procedure adopted takes into account the aspects mentioned above and uses monitoring data from one of the MCL cells over a period of 44 months and the results of laboratory tests carried out on the MSW to perform the water balance.

2. Description of the adopted water balance method

The water balance was computed incrementally dividing the period analyzed into several time intervals according to the disposal scenario and the region considered (if cover layer or RSU mass). The horizontal dimensions of the landfill are assumed to be much greater than the height in such a way that uni-dimensional equations can be used to adequately describe the water balance.

The input flows are considered only at the top of the cell (bottom and lateral slopes are considered impervious). The input components considered in the model are the amount of rainfall and the initial water contents of the MSW and the cover layer. The output components considered are evaporation, superficial flow, water consumption by biodegradation processes, leachate collection and the release of water vapor during biogas extraction.

Fig. 1a and b illustrates two scenarios used to derive the water balance equations. The differences in these scenarios are related to the use (1a) or not (1b) of soil cover layers. Input and output

components in each situation are also presented in these figures, where RA refers to the amount of rain, E is the evaporation, RO is the runoff or superficial flow, $I_{(soil)}$ is the water infiltration in the soil cover layer, $I_{(MSW)}$ is the water infiltration in the MSW and L is the volume of collected leachate. $\Delta\theta$ is related to the changes in the volume of stored water in the system and $\theta_{i(soil)}$ and $\theta_{i(MSW)}$ are the initial volumetric water contents of the soil cover and MSW, respectively. These values are used to compute the amount of water that enters the cell with the cover soil and MSW.

2.1. Cover layer water balance

In the case of the use of a soil cover layer in the cell (Fig. 1a), part of the rainfall water may flow superficially. Therefore not all the rainfall volume will enter the system. Eq. (1) summarizes the water balance in this case

$$RA + \theta_{i(soil)} \cdot \Delta z_{(soil)} = RO + E + \Delta\theta_{(soil)} + I_{(MSW)} \quad (1)$$

where $\Delta\theta_{(soil)}$ (–) is the change in the volumetric water content of the soil cover and $\Delta z_{(soil)}$ (L) is the thickness of the cover layer. RA, RO, E and $I_{(MSW)}$ are considered in terms of an equivalent column of water (L).

In the proposed model runoff is calculated as a function of the rain intensity ($\partial RA/\partial t$) and the infiltration capacity of the soil ($\partial I_{(soil)}/\partial t$), as presented in Eq. (2). The volume of infiltrated water, $I_{(soil)}$ (L), is calculated using the Eq. (3) proposed by Philip (1957). If the soil infiltration capacity is lower than rain intensity, there will be runoff. If not, runoff will be zero and the infiltration rate will be equal to rain intensity

$$\frac{\partial RO}{\partial t} = \frac{\partial RA}{\partial t} - \frac{\partial I_{(soil)}}{\partial t} \quad (2)$$

$$I_{(soil)}(t) = S \cdot t^{1/2} + A_k \cdot t \quad (3)$$

where t is the elapsed time (T) and A_k (L/T) is the adjusted soil permeability (k_{sat}). According to Philip (1990) $0.5 \leq A_k \leq (2/3) k_{sat}$. S ($L T^{-1/2}$) is the water absorption capacity of the soil considering its initial water content. The S parameter is obtained by Eq. (4), in which h_{surf} (L) is the water head above the soil surface, considered as zero in this paper (no ponding); h_o (L) is the suction head (negative pressure head) at the initial water content (θ_o) of the soil and θ_f (–) is the final volumetric water content of the soil

$$S^2 = 2k_1[h_{surf} - h_o][\theta_f - \theta_o] \quad (4)$$

θ_f is assumed as $0.9 \cdot n$ (soil porosity) obtained using the physical soil indices. This is in accordance with experimental evidence reported by several authors that soil is not fully saturated in the wetting front. Eq. (5) is used to calculate the changes in the volumetric water content of the cover layer, which are used to update the amount of water content of the soil in each time interval

$$\Delta\theta_{(soil)} = (I_{(soil)} - E)/\Delta z_{(soil)} \quad (5)$$

The values of h_o and θ_o are related according to the soil retention curve determined in the laboratory and fitted using Eq. (6), proposed by Van Genuchten (1980)

$$\theta_{soil} = \theta_r + \frac{\theta_{sat} - \theta_r}{[1 + |\alpha h_o|^{m_v}]^{1/m_v}} \quad (6)$$

where θ_r (–) and θ_{sat} (–) are the soil residual and saturated volumetric water contents and α (L^{-1}), m_v (–) and n_v (–) are fitting parameters. In the fitting process m and n were considered dependent, according to Eq. (7)

$$m_v = 1 - \frac{1}{n_v} \quad (7)$$

Fig. 1. Physical model adopted for the proposed water balance. (a) With cover layer and (b) without cover layer.

For cover layer water balance, it is considered that:

- (a) if $[\theta_{(soil)} + \Delta\theta_{(soil)}]$ is lower than the soil–water content at field capacity ($\theta_{cc(soil)}$), all infiltration will be retained in the cover layer and this amount will be assumed as the value of $\theta_{(soil)}$ in the following time interval. In this case, the water will not infiltrate into the MSW ($I_{(MSW)} = 0$).
- (b) else, $[\theta_{(soil)} + \Delta\theta_{(soil)}] = \theta_{cc(soil)}$.

The time intervals used in the cover layer water balance were 1 h. In order to do this all the field data were converted to a hourly basis. Field capacity was assumed as the soil–water content for $h_o = -3.3$ m. Eq. (8) calculates infiltration into the MSW mass. Values of $I_{(MSW)}$ are used as input data for the MSW water balance. Fig. 2 presents a flow chart which illustrates how the water balance for the cover layer is calculated

$$I_{(MSW)} = I_{(soil)} - E + (\theta_{cc(soil)} - \theta_{i(soil)}) \cdot \Delta z_{(soil)} \quad (8)$$

The water evaporation (E) rates in the cover layer were estimated using the results of evaporation experiments performed in field. Undisturbed samples were collected in order to determine the dry density and water content at different points of the cover layer of the cell. The soil samples were then compacted using average field conditions of dry density and optimum water content (normal Proctor Energy). Field evaporation tests are carried out using always two reservoirs simultaneously, one filled with compacted soil and the other with water. The water reservoir is designed to reproduce potential evaporation conditions (E_p) while the soil reservoir is designed to reproduce the evaporation conditions in the soil cover (E) under the same weather conditions. Experimental results of the evaporation rates in soil (E) and water (E_p) are compared and the curves $E/E_p \times \theta_{(soil)}$ determined. The ratio E/E_p is used to transform the potential evaporation (E_p) values obtained in the weather station into soil evaporation values (E). When there is no experimental data, the models proposed by Penman (1948) and Wilson (1990) can be used to estimate the values of E/E_p , as described in São Mateus (2008).

2.2. MSW global water balance (use of soil cover layer)

Eq. (9) is used in the MSW global water balance. It considers the input and output of liquids in the cell and quantifies the

Fig. 2. Flow chart illustrating the process of calculus of the water balance for the cover layer.

accumulated volume without separating free water from water bonded to the MSW solid particles. The time intervals used in the MSW water balance corresponded to 1 day and to do this all the field data was converted to a daily basis

$$\theta_{(MSW)} \cdot Z_{(MSW)} = I_{(MSW)} + \sum \theta_{i(MSW)} \cdot \Delta z_{(MSW)} - L/A_{(MSW)} - V_{w \text{ biodeg}}/A_{(MSW)} - V_{w \text{ vapor}}/A_{(MSW)} \quad (9)$$

where $\theta_{(MSW)}$ (–) is the MSW average volumetric liquid content; $V_{w \text{ biodeg}}$ (L^3) is the volume of water consumed in the biodegradation process; $V_{w \text{ vapor}}$ (L^3) is the volume of water extracted from the landfill with the biogas; L (L^3) is the collected volume of leachate; $A_{(MSW)}$ (L^2) is the cross-section of the landfill cell; $\Delta z_{(MSW)}$ (L) is the thickness of each disposed layer of MSW in the cell; $z_{(MSW)}$ (L) is the total thickness of the MSW in the cell (L).

Eq. (9) is similar to the equation adopted by Blight et al. (1997) but it considers the water losses in the biodegradation processes and the input of water with MSW each time it is disposed in the landfill.

Table 2, proposed by Machado et al. (2009), is used to calculate the MSW loss of mass and the values of $V_{w \text{ biodeg}}$. In Table 2 C_m represents the methane generation per MSW dry mass of effectively degraded material. This was obtained using stoichiometric equations which assume a complete conversion of organic matter to gaseous products. The water consumption factor was determined in a similar manner to C_m . Values of C_m for the waste as a whole can be calculated using the waste composition (dry basis), as described by Machado et al. (2009). Once the values of C_m and water consumption are calculated, the methane production of the cell is used to calculate the MSW loss of mass (dry basis) and the water consumption due to biodecomposition.

Eq. (10) calculates the water vapor that leaves the landfill with the extracted biogas ($V_{w \text{ vapor}}$). Where P_v is water vapor pressure ($M T^{-2} L^{-1}$) for the given temperature; V is the volume of extracted biogas (L^3); R is the gas universal constant ($8.314 M T^{-2} L^2/mol K$); T is the biogas temperature (K) and n_m is the number of moles of water vapor that leave the landfill (mol)

$$P_v \cdot V = n_m \cdot R \cdot T \quad (10)$$

After the calculation of the global water balance of the cell using Eq. (9), it is possible to separate the accumulated volume of liquid into liquid associated or bonded to the MSW ($\theta_{ads(MSW)}$) and free liquid ($\theta_{(free)}$) as stated in Eq. (11)

$$\theta_{(MSW)} = \theta_{ads(MSW)} + \theta_{(free)} \quad (11)$$

Free liquid is responsible for the leachate flow inside the landfill body and its level can be measured by piezometers installed in the cell. Eq. (12) is used to calculate $\theta_{ads(MSW)}$. In this equation $\Delta\theta_{comp(MSW)}$ is the volumetric water content variation due to MSW compression (–) and water expelling; $V_{w \text{ decomp}}$ represents the volume of liquid that becomes free to flow as a result of MSW degradation (L^3) and $V_{(MSW)}$ is the MSW overall volume (L^3)

$$\theta_{ads(MSW)} = \theta_{i(MSW)} + \Delta\theta_{comp(MSW)} - V_{w \text{ decomp}}/V_{(MSW)} \quad (12)$$

Table 2

Depleted dry mass of MSW to biogas conversion factor, C_m (adapted from Machado et al., 2009).

MSW biodegradable components	Water consumption (average) (Mg H ₂ O/Mg degraded dry MSW)	C_m (average) (m ³ CH ₄ /Mg degraded dry MSW)
Food/garden waste	0.27	493.36
Paper/cardboard	0.18	428.61
Wood	0.24	484.94

In order to obtain $V_{w \text{ decomp}}$ the methane production of the cell and the value of C_m are used to calculate the MSW loss of mass and the water consumption. Considering only the mass of decomposed MSW, $V_{w \text{ decomp}}$ corresponds to the MSW water content before its decomposition, minus the liquid consumed by the decomposition process. It represents the excess water in the MSW compared to the water necessary for biodegradation to occur. Values of $\Delta\theta_{comp(MSW)}$ are calculated using the laboratory results of confined compression tests and the values of vertical stress during the cell filling process.

The results of the confined compression tests are also used to calculate the values of void ratio and saturation degree of the waste over time. Effective stress at the average height of the water table was calculated using Eq. (13) below, proposed by Shariatmadari et al. (2009) for materials with compressible solid particles

$$\sigma' = \sigma - A \cdot u_w \quad (13)$$

where A is a function of the ratio between the overall compressibility of the waste and the average compressibility of waste particles. Fig. 3 presents some results obtained by Shariatmadari et al. (2009) for waste samples with different fiber contents (FC). As can be noted, values of A decrease with mean stress, p , and increase with the fiber content of the waste. Fig. 4 presents a flow chart which illustrates the process of calculus of the water balance in the MSW.

2.3. MSW global water balance, without a cover layer

In these conditions the proposed model considers that all the rain infiltrates into the MSW mass. This assumption is based on the high permeability of the MSW for shallow depths and its large voids which prevent the occurrence of runoff. Because of the low water retention capacity of the MSW, it is considered that soil evaporation (E) is equal to potential evaporation (E_p) or $E/E_p = 1$, regardless of the MSW water content. Eq. (14) describes the MSW global water balance without the cover layer. The procedure to separate free and associated water is the same as presented before

$$R + \sum \theta_{i(MSW)} \cdot \Delta z_{(MSW)} = E + L/A_{(MSW)} + \theta_{(MSW)} \cdot Z_{(MSW)} + V_{w \text{ biogas}}/A_{(MSW)} + V_{w \text{ vapor}}/A_{(MSW)} \quad (14)$$

3. Application of the adopted water balance method

The proposed method was applied to calculate the water balance of cell number 5 at the metropolitan center landfill (MCL) in Salvador, Bahia, Brazil.

3.1. Characteristics of the cell and landfilling process

The cell to which the water balance was applied had nominal dimensions at the soil surface of 135×301 m. The bottom cell was about 10.5 m below the soil surface. Nominal dimensions of the cell at the bottom were 109×276 m. The construction of the cell was finished in March 2003 and the first phase of the landfilling process occurred from May 2003 to May 2004. In this period about 813,000 Mg of MSW were deposited in the cell. The average MSW thickness at the end of this phase was 22 m. A soil cover layer of an average thickness of 57 cm was then placed over the MSW (temporary cover) and the cell remained inactive, i.e., without any further MSW disposal until August 2005. According to Machado et al. (2009), during this period the temporary cover was partially replaced by a final cover. A PVC-geotextile membrane (PVC-GM) is used as a final cover over the soil layer and about

Fig. 3. Variation of the parameter A with mean stress Shariatmadari et al. (2009).

cover layer was installed in March 2006 over the whole cell surface. The total amount of MSW disposed in the cell was about 1,055,000 Mg. The temporary soil cover was removed before restarting the landfilling process.

3.2. Field tests, measurements and activities

MSW samples of fresh waste were collected at the disposal front. Three sampling campaigns were performed in the landfill during the cell operation period. Samples containing about 100 kg of waste were used in the MSW characterization while samples of about 20 kg were used to determine the water content of the waste. Waste composition, wet basis, was determined just after sampling in a field laboratory using some basic tools (oven, balance, trays, masks, gloves, plastic bags, etc.). Waste components were separated into the following groups: paper/cardboard, plastic, rubber, metal, wood, glass, ceramic materials/stone, textiles and paste fraction. The paste fraction includes organic materials which are easily degradable (food waste), moderately degradable (e.g., leaves) and other materials which were not easily identifiable. After separation, each component was promptly stored in sealed plastic bags and weighed. Waste composition, dry basis, was determined after drying at 70 °C. This procedure enabled the determination of the waste composition on dry and wet basis and the water content of each component. The water content was determined for each component and for the waste as a whole. The water content of the waste as a whole was obtained using: (a) the waste dry composition and the individual values for the water content of each component, and (b) the samples of waste in its natural state. These values were used to check the efficacy of the measures taken in order to avoid water loss from the samples. More details about the MSW characterization procedure can be found in Machado et al. (2009). All the values of water content presented in this paper refer to gravimetric water content, dry basis.

Field measurements such as weight of disposed waste, volume of collected leachate, methane production and biogas temperature were performed. The level of free water (leachate) inside the cell was monitored using Vector piezometers which are able to measure gas pressure and leachate level separately (Antoniutti Neto et al., 1995).

Several measurements of dry unit weight and water content were performed at different locations on the soil cover layer. Evaporation tests were carried out on compacted samples of the cover layer soil. Samples were compacted in the average field value of dry unit weight and optimum water content for Proctor Normal energy. Two PVC cylindrical recipients with nominal dimensions of 157 mm diameter and 148 mm height were used to simultaneously perform evaporation tests on compacted samples and water. Soil samples were saturated and then submitted to evaporation. Evaporation tests were carried out measuring the daily loss of water in the two recipients. The daily evaporation rates (E and E_p) were calculated for soil and water and the curves $E/E_p \times \theta_{(soil)}$ were determined. Values of $\theta_{(soil)}$ were back calculated after the end of the tests, using the performed measurements of loss of mass.

3.3. Laboratory tests

Samples of the cover layer soil underwent characterization tests such as solids specific weight, grain size curves and Atterberg limits (ABNT NBR 6508, 1984; ABNT NBR 7181, 1984; ABNT NBR 6459, 1984; ABNT NBR 7180, 1984), compaction tests (ABNT NBR 7182, 1986) and permeability tests (ABNT NBR 13292, 1995; ABNT NBR 14545, 2000). Soil–water retention curve tests were also performed on undisturbed soil cover samples trimmed from the cover layer at a depth of 20 cm in varying locations, using the experimental procedure proposed by Machado and Dourado (2001).

Fig. 4. Flow chart illustrating the process of calculus of the water balance for MSW.

20 cm of organic soil is installed over it for grass support. Superficial drains are located above the soil layer of the final cover and beneath the PVC-GM and serve to collect the biogas accumulated in this region and to minimize possible fugitive emissions due to PVC-GM non-conformities. The second phase of landfilling occurred from September 2005 to February 2006 and the final soil

The volatile solids content of the MSW paste fraction was obtained by quartering the paste mass into portions of about 1000 g and grinding them to reduce the size of particles and to increase the specific surface. Paste samples containing about 20 g were placed into crucibles and dried in an oven at 70 °C for 1 h. Samples were then combusted in a muffle at 600 °C for 2 h. After that, VS values were computed using the ratio between the loss of mass and the dry mass before combustion.

The specific unit weight of the MSW solid particles, γ_s , was determined using applicable standards (ABNT NBR 6508, 1984) using a representative portion of MSW that was ground after drying.

A confined compression test was performed using an oedometer with nominal dimensions of 548.3 mm diameter and 496.8 mm height. Fresh waste was statically compacted in three layers until the unit weight of 7.11 kN/m³ was reached ($e_0 = 4.2$). This value is similar to that obtained in the field just after compaction. The initial water content of the samples was 113.7% (dry basis). The test was performed in a conventional manner with six loading stages from the initial value of vertical stress (20 kPa) to the maximum vertical load applied (640 kPa). The test lasted about five months. During the compression test as well as the conventional measurements, the amount of expelled liquid from the sample was monitored. Confined compression results were used in the model to calculate the contribution of the water that enters the cell with MSW to the volume of free water. Furthermore, the MSW confined compression curve ($e \times \sigma'_z$) was used to calculate the leachate level from the volume of free water estimated by the water balance.

4. Results and analysis

4.1. Soil cover layer

Laboratory permeability tests performed in the cover layer presented an average value of $k_{sat} = 8.33 \times 10^{-7}$ cm/s, with standard deviation of 3.87×10^{-7} cm/s. The average water content and the dry density of the soil cover layer were $w = 9.56\%$ and $\rho_d = 1.6$ g/cm³, leading to an average field volumetric water content of $\theta_{i(soil)} = 0.153$. The standard compaction tests presented average results of maximum dry density of $\rho_{dmax} = 1.90$ g/cm³ and optimum water content of $w_{ot} = 11.6\%$. Soil particles presented an average value of specific unit weight of $\rho_s = 2.728$ g/cm³. Grain-size analysis indicated that the cover soil is composed of 72% sand, 1.9% silt and 26.1% clay and the soil was classified as SC, by USCS.

Fig. 5 shows the results obtained from the evaporation tests. As can be observed the ratio of daily evaporation rates (E/E_p) varied linearly with the water content of the soil ($\theta_{(soil)}$). Only one experimental point showed a discrepancy from the observed linear trend and was discarded from the fitting process.

Fig. 6 presents the soil retention curve obtained considering the experimental points of all the tested samples. Despite the scattering of the results (which was expected because the samples presented different values of porosity) there is a fair adjustment of Eqs. (6) and (7) to the experimental results. Values of $\theta_{sat} = 0.423$, $\theta_r = 0.072$, $m = 0.29$, $n = 1.41$, $\alpha = 0.135$ (cm⁻¹) and $R^2 = 0.82$ were obtained from the fitting process.

4.2. Landfill cell and MSW

Fig. 7 presents the accumulated amounts of rainfall water, collected leachate and water that enters the cell with the MSW. Rainfall water volume (376,000 m³) was calculated considering the amount of rain in the period (L) times the cell surface at ground level (L²). The volume of water that entered the cell with the MSW until 03/2006 was about 522,000 m³, despite the fact that

during the period from June 2004 to August 2005 there was no waste disposal. This value was calculated using a mass of disposed waste of 1,055,000 and average water contents of 93%, 83% and 122% for the years of 2003/2004, 2005 and 2006, respectively, and it is greater than the rainfall volume and the volume of collected leachate (about 349,000 m³).

Fig. 8 presents the methane generation rate in the cell during the period from May 2003 to December 2006. As can be observed, the methane generation rate increased from about 830 m³ CH₄/h in May 2003 to almost 1900 m³ CH₄/h in March 2006. From January 2005 to August 2005 there was a decrease in the methane generation rate. In this period no waste was disposed in the cell. The same occurred after cell closure. The methane generation rate decreased continuously, reaching about 930 m³ CH₄/h in December 2006. A sharp decrease in the methane generation rate after cell closure was already expected due to the high values of the constant related to the biodegradation rate ($k = 0.21$), as reported by Machado et al. (2009). Fugitive emissions were considered according to what is described in Machado et al. (2009). Measurements of gas temperature at the exit of the drains did not show any clear trend of variation over time. Average temperature values (considering all the drains installed in field) ranged from 30 to 35 °C.

Table 3 shows the average MSW gravimetric composition (dry basis) for the MSW samples of fresh waste collected during the period of operation of the cell. Data presented in Table 3 were used to calculate the values of C_m for the waste as a whole. An average value of $C_m = 479.67$ m³ CH₄/Mg dry mass of depleted MSW was obtained. The value of C_m and the gas generation rates presented in Fig. 8 were used to calculate the MSW loss of mass and the water consumption due to the biodegradation process (see Table 2). Furthermore, using Eqs. (11) and (12), the excess water present in the waste at the moment decomposition occurred was transformed into free water. An average value of specific unit weight of $\gamma_s = 17.5$ kN/m³ was obtained.

The results of the confined compression tests are shown in Figs. 9 and 10. Fig. 9 shows the confined compression curve obtained for the MSW. The results presented in Fig. 9 were fitted by Eq. (15), proposed by Balmaceda et al. (1992), where λ , e and N are the MSW compression index, void ratio and specific volume for $\sigma_z = 1$, respectively. Fig. 10 presents the variations in the water content of the sample as a result of waste compression (water expelling from sample). Tests were carried out without water addition or leachate recirculation in the MSW. It can be noted that there is a significant reduction in the MSW water content with applied vertical stress and that the rate of loss of water of the sample by compression decreases with vertical stress. The sample presented an initial water content of 113.70% (dry basis). After 640 kPa of applied vertical stress this amount fell to 44.64%. Considering the geometry of the cell after waste disposition (March 2006), an average value of effective vertical stress of about 170 kPa can be calculated, leading to average values of $e = 1.61$ and $-\Delta w = 42\%$

$$e = \frac{N}{\sigma'_z} - 1 \quad (15)$$

4.3. Water balance

The figures below illustrate some results obtained with the performed water balance of the MCL Cell. Fig. 11 presents the calculated outputs of water of the system. From May 2003 to May 2004, due to the non-existence of soil cover layers, evaporation was assumed as equal to evaporation potential $E/E_p = 1$. Table 4 presents average values of E_p from 1961 to 1990 in Salvador, Bahia. From June 2004 onwards evaporation was calculated using data presented in Fig. 5 and considering the ratio between the area

Fig. 5. Variation of the ratio of daily evaporation rates (E/E_p) with $\theta_{(soil)}$.

Fig. 6. Average soil retention curve.

Fig. 7. Accumulated volumes of water in the cell.

using an intermediate cover layer and the total area of the cell. Evaporation was considered negligible in areas where the final cover of soil was installed. Using numerical integration, an average value of $E/E_p = 0.37$ was obtained for the intermediate soil cover in the field from May 2003 to December 2006. From September 2005 to February 2006 a new disposal phase occurred in the cell. As the soil

cover was removed prior to landfilling $E/E_p = 1$ in the disposal area was considered, corresponding to about 42% of the cell surface. According to Fig. 11, leachate accounted for 78% of the output of liquids of the cell. Evaporation corresponded to 16% and the water consumed in the organic matter depletion processes was about 6% of the liquid output. The amount of water extracted with biogas was negligible.

Fig. 12 presents the main inputs of water in the system. As can be seen from this figure, the amount of water that was considered to infiltrate into the MSW ($I_{MSW} = 214,000 \text{ m}^3$) corresponded to only 29% of the water that enters in the cell. The remaining water entered in the cell with MSW ($\sum \theta_{i(MSW)} \Delta z_{(MSW)} = 522,000 \text{ m}^3$). The volume of water that infiltrated in the cell was about 57% from the rainfall in the period considered (see Fig. 7).

Fig. 13 compares the total inputs and outputs of liquid in the cell. According to the obtained data, the total input of water in the system was about $736,000 \text{ m}^3$ and the output corresponded to about $425,000 \text{ m}^3$ of water/leachate, resulting in a $311,000 \text{ m}^3$ net input of water in the system. The variation of the net input of water over time is shown in Fig. 14. In this figure the volume of free water of the cell is also shown. On 31st December 2006, the total volume of water in the cell was estimated at about $311,000 \text{ m}^3$ and the volume of free water was about $57,000 \text{ m}^3$ (18.4% of the total water). At the end of the period analyzed the waste underwent a water content loss of about 42% by compression. This means that about

Fig. 8. Methane generation rate.

Table 3
MSW average gravimetric composition (dry basis).

Components	% of each component (dry basis)		
	Average (%)	Standard deviation	Coefficient of variation (%)
Plastic	22.45	5.10	22.7
Paste fraction ^a	34.68	5.73	16.5
Textile/rubber	3.09	1.47	47.6
Paper	14.91	5.90	39.5
Glass	3.67	1.80	49.1
Wood	4.73	3.17	67.0
Metal	2.78	1.84	66.2
Stone/ceramic	13.36	6.41	48.0

^a Paste fraction includes organic materials which are easily degradable (food waste), moderately degradable (e.g., leaves) and other materials which are not easily identifiable.

Fig. 9. MSW confined compression curve.

237,000 m³ of water was expelled from the waste mass, becoming free water. As this amount is higher than I_{MSW} , it can be said that most of the free water in the cell enters the system with the MSW.

The total amount of MSW stored in the cell (dry basis) was about 499,000 Mg. The final average water content of the MSW above the water table, calculated using data presented in Fig. 14, was about 60%. If the presence of the MSW inside the cell is ignored, the 57,000 m³ of free water would be responsible for a

Fig. 10. MSW water content variation during confined compression test.

Fig. 11. Accumulated exit of liquids of the cell.

water table height of about 1.81 m. However, MSW below the water table presents an average value of void ratio of $e = 1.53$ ($n = 0.61$) and an initial average saturation degree (S_r) of about $S_r = 54\%$. This leads to a water table height of about 6.51 m at the end of the water balance period.

Fig. 15 presents the water table height predicted by the water balance and the experimental values measured by the two piezometers installed in the cell. As can be observed, the performed water balance was able to capture the main trends of the values measured in the field. It must be said, however, that experimental values presented smooth variations over time compared to predicted results and that the differences in the water table height measured by the two piezometers are significant. This had been expected, at least in part, as the water needs time to flow down to the bottom of the cell. Another aspect worth mentioning is that the movement of water inside the waste mass is influenced by the heterogeneity of the waste mass, gas pressure, the efficiency of the drainage system, etc., all of which help to explain the differences obtained between the experimental and predicted results.

5. Conclusions

This paper presented an attempt to model the water balance in a Brazilian municipal solid waste landfill. The proposed method considers some aspects which are not usually considered in other approaches to water balances, such as the calculation of the amount of water expelled from the waste mass by compression and the separation of the stored water in the system into free water and water attached to the waste.

Table 4
Monthly average values of E_p . 1961–1990 series. Salvador, Bahia.

Month	January	February	March	April	May	June	July	August	September	October	November	December
E (mm)	93.5	84.0	87.2	74.0	71.5	82.1	89.6	90.2	87.1	85.6	83.7	84.3

Fig. 12. Accumulated input of liquids of the cell.

Fig. 15. Water table height. Predicted and experimental results.

Fig. 13. Total input and output of liquids of the cell.

Fig. 14. Net input of water versus free water in the cell.

A cell at the metropolitan center landfill was used to apply the proposed water balance. Aspects such as the MSW initial water content, mass loss due to decomposition, MSW liquid

expelling due to compression, and those related to weather conditions, such as the amount of rainfall and evaporation, were considered.

The obtained results led to the conclusion that most of the water (71%) that entered the cell was due to waste water content of the MSW. The amount of water that infiltrated MSW (about 57% of the rainfall water in the period considered) corresponded to only 29% of the total input of water. This means that even in the case that all the rain infiltrates the waste mass, the amount of water that enters the cell with the MSW will be the main input of water in the system.

Considering the outputs of water, leachate corresponded to 78% of the output liquids of the cell. Evaporation corresponded to 16% and the water consumed in the organic matter depletion processes was about 6% of the liquid output. The amount of water extracted with biogas was negligible. The procedure adopted to transform potential evaporation into soil evaporation was very useful and easy to perform in the field. An average value of $E/E_p = 0.37$ was obtained for the intermediate soil cover in the field from May 2003 to December 2006.

The total input of water in the system was about 736,000 m³ and the output corresponded to about 425,000 m³ of water/leachate, resulting in 311,000 m³ of net input of water in the system, 57,000 m³ (18.4%) of it in the form of free water. The waste underwent a water content loss of about 42% through compression. This means that about 237,000 m³ of water was expelled from the waste mass to become free water. This is higher than the volume of water that infiltrated into the MSW (I_{MSW}).

The performed water balance was able to capture the main trends of the values measured in the field. It must be said, however, that experimental values presented smooth variations over time compared to predicted results and that the differences in the water table height measured in the two piezometers were not negligible. This had been expected, at least in part, as the water requires time to flow down to the bottom of the cell. Another aspect worth mentioning is that the movement of water inside the waste mass is influenced by the heterogeneity of the waste mass, gas pressure, the efficiency of the drainage system, etc., all of which go towards explaining the differences obtained between the experimental and predicted results.

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