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Performances analysis of the sanitary landfill's final dry cover using numerical modeling

Análise do desempenho da cobertura final de aterros sanitários utilizando modelagem numérica

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Abstract: This work aims to determine the performance of the final coverage of landfills located in the Metropolitan Region of Fortaleza-CE, by determining the water balance portions and saturation and pore pressure profiles, using numerical modeling of the water flow of the water balance. Numerical modeling was carried out with the help of Vadose/W Software considering periods of different years with higher and lower rainfall. According to the water balance plots, all models analyzed presented high percolation values. Therefore, the model with a coverage of 30 cm of natural soil was selected for water flow analysis, considering that it was the configuration used in the landfill where the data used in this work were obtained. Considering the analysis of saturation and pore pressure profiles, the model in question did not present good performance for application in the final layers of landfills, given its inability to maintain saturation conditions in rainy and dry seasons, which would allow the occurrence of exit of the gas flow from inside the system. Numerical modeling proved to be a viable tool in analyzing the performance of urban solid waste-land cover systems, helping to quickly predict their behavior.

Keywords: Water Flow; Hydric Balance; Sanitary Landfill.

Resumo: Este trabalho visa determinar o desempenho da cobertura final de aterros sanitários localizados na Região Metropolitana de Fortaleza-CE, através da determinação das parcelas de balanço hídrico e de perfis de saturação e de poropressão, utilizando modelagem numérica do fluxo de água do balanço hídrico. As modelagens numéricas foram realizadas com auxílio do *Software* Vadose/W considerando períodos de anos distintos de maior e de menor precipitação. De acordo com as parcelas de balanço hídrico, todos os modelos analisados apresentaram valores elevados de percolação. Deste modo, o modelo com cobertura de 30 cm de solo natural foi selecionado para análise de fluxo de água, tendo em vista ser a configuração empregada no aterro sanitário onde foram obtidos os dados utilizados neste trabalho. Considerando as análises de perfis de saturação e de poropressão, o modelo em questão não apresentou bom desempenho para aplicação em camadas finais de aterros sanitários, dada a sua incapacidade de manter as condições de saturação em épocas chuvosas e secas, o que permitiria que ocorresse a saída do fluxo de gases do interior do sistema. A modelagem numérica se mostrou uma ferramenta viável na análise de desempenho dos sistemas do tipo resíduos sólidos urbanos-cobertura de solo, auxiliando na previsão do seu comportamento rapidamente.

Palavras-chave: Fluxo de água; Balanço Hídrico; Aterro Sanitário.

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1. Introduction

The environmentally appropriate disposal of Urban Solid Waste (MSW) continues to be one of the biggest challenges within basic and environmental sanitation in the country (Santos, 2008). This concern is mainly due to the high volume of MSW produced, which is directly related to population growth combined with intense urbanization and the increase in purchasing power linked to the emergence of new technologies (Silva et al., 2020). In many cases, this waste is disposed of in inappropriate locations, negatively impacting the environment. Among the disposal alternatives, the sanitary landfill is considered an environmentally appropriate method for the treatment and final disposal of MSW. However, the degradation of waste caused by physical, chemical and biological mechanisms occurring in these locations, transforms organic matter into leachate and gases (Rocha; Rosa; Cardoso, 2009). This degradation creates preferential paths for liquids in the material, facilitating the conduction of leachate within the waste mass and allowing gases to escape.

Dry cover systems are a viable alternative in the control of these soluble and gaseous materials and consist of applying layers of soil, geosynthetics and alternative materials over the waste. This system acts to contain waste and the compounds generated by it, by controlling the entry of water and air into the mass of waste, resulting in lower costs to effluent treatment (Joaquim Júnior, 2015).

The knowledge about the long-term performance of dry cover is extremely important, considering that these systems can suffer significant changes in water content as a result of seasonal cycles, leading to wear and tear in the long term due to increased hydraulic conductivity and, consequently, increased infiltration (Albright, B.; Waugh, 2010; Mellies; Schweizer, 2015; Wang; Xue; Liu, 2014; Lu et al., 2015). However, results from a physical model can take months to years and have limitations about instrumentation.

Therefore, numerical solutions are commonly used to obtain a faster and more reliable prediction of coverage performance. The numerical model simulates a real physical process and to guarantee accurate modeling it is essential to have an excellent representation of the input parameters about the materials and conditions to which the dry cover will be subjected. Numerical models provide information on the entire profile and also allow the simulation of different boundary conditions and geometries.

Several researchers have sought to evaluate the performance of dry roofs through the use of numerical modeling (Borghetti Soares, A. et al., 2009; Borghetti Soares, A. et al., 2015; Souza et al., 2019). In the international context, it is noticeable the work of Widomski et al. (2015); Saito et al., (2021); Alam et al. (2021), among others. In general, the authors emphasize that numerical modeling helps in predicting the behavior of landfills, and that the results obtained allow evaluating their performance.

Borghetti Soares et al. (2009) used numerical modeling with the Soil Cover program to design covers to cover coal mining tailings. Numerical modeling led to the selection of four configurations for testing: a dry cover with a double capillary barrier with bottom ash, a dry cover with a single layer of clay, and a dry cover with mixed residues and residues without cover. The modeling results made it possible to select the best-performing model to be applied and monitored in the field on a pilot scale.

Borghetti Soares et al. (2015) studied the water flow and water balance of tailings-cover systems through numerical modeling, using the Vadose/W software that considers the evapotranspiration flow. The numerical modeling was developed for two physical models of the tailings type, built in a pilot unit, located in a coal mine, in Santa Catarina State. The modeling results showed good performance of the coverings, given the reduction in percolated volumes and the maintenance of high degrees of saturation in the clay layer, and they agree with the data obtained in the field.

Souza et al. (2019) evaluated infiltration in experimental models of dry roofs using coal ash from the Pecém Thermoelectric Plant. In their research, three coverage models were produced: Column A – An upper layer of natural soil (30 cm) and a layer of waterproofing material with a mixture of soil and ash MS70C30 (30 cm, with 70% soil and 30% ash); Column B – A layer of natural soil (30 cm) and a layer of waterproofing material with composite ash (30 cm); and Column C – Single layer of natural soil (30 cm), representing the coverage found in the Sanitary Landfill of the Municipality of Caucaia. The results show that the percolated volume in each test, the one that performed best was the MS70C30 mixture (Column A), resulting in a much lower percolated volume compared to the other two models. The material also maintained high saturation conditions, above 90% throughout almost all tests, a necessary condition to reduce the leakage of biogas from inside the system.

Widomski et al. (2015) carried out numerical modeling of the water balance to simulate the performance of a temporary landfill cover in the North of Germany. The authors used the FEFLOW 6.0 program. According to the results of the water balance components, the temporary stratified landfill cover system performed well, considering that they presented a coefficient of determination between 0.50 and 0.90 for calculated volumetric water content values and measurements. According to the authors, the deviation between measured and modeled values is related to soil heterogeneity.

Saito et al. (2021) accomplished numerical modeling using the Hydrus program, in order to estimate the volume of leachate produced in an MSW landfill located in Rio de Janeiro. The authors modeled four types of final cover: vegetation cover by grasses; vegetation cover by brachiaria; compact soil cover; and capillary barrier coverage. The results indicated that the vegetation cover composed of grasses and brachiaria presented important control mechanisms regarding the movement of the contaminating plume. The best performances for the final landfill coverage were achieved with the capillary barrier, while the worst were obtained with the compact soil commonly used.

Alam et al. (2021) compared water balance predictions made with a numerical model and field data from a monolithic cover of a landfill located in Texas (USA). Therefore, local climatological data, properties of the protective vegetation layers measured in the field and the hydraulic properties of the covering materials were used. Based a preliminary simulation of one-year data, the numerical model reasonably predicted the water balance components. However, the percolated volume was underestimated by the numerical model, one hypothesis for this discrepancy is due to the presence of preferential flow paths (desiccation cracks), which the numerical model cannot reproduce.

It is observed that numerical modelings are useful tools that allow simulation the complex interaction of the coverage-residue system. From this perspective, this work aims to determine the performance of the final cover, which is generally applied in Brazilian landfills, by determining the water balance portions and saturation and pore pressure profiles, using numerical modeling of the water flow of the water balance. The models developed are representative of the types of dry covers for landfills used in Brazil and the input parameters to feed the numerical program are representative of covering materials and MSW and were obtained experimentally.

2. Methodology

The numerical models were reproduced in the Vadose/w software (Geostudio, 2007), which is a two-dimensional program based on finite elements, that allows the simulation of water flow in porous media through stationary and transient regimes, as well as water balance. in cover-reject systems (Geostudio, 2007). Vadose/w has been used in different research to simulate the flow of evapotranspiration and water balance in unsaturated soils (Borghetti Soares, A. 2013, 2022; Souza, 2018).

The numerical models were developed to reproduce a layer composed of a single material in the final cover of an urban solid waste landfill, which is a common practice applied in some Brazilian landfills. Three models were produced with a 1 m deep MSW layer, varying the thickness of the covering layer to 20, 30, and 40 cm (Figure 1). The choice of the thickness variation of the covering layer occurred because these are the dimensions generally used in Brazilian urban solid waste landfills.

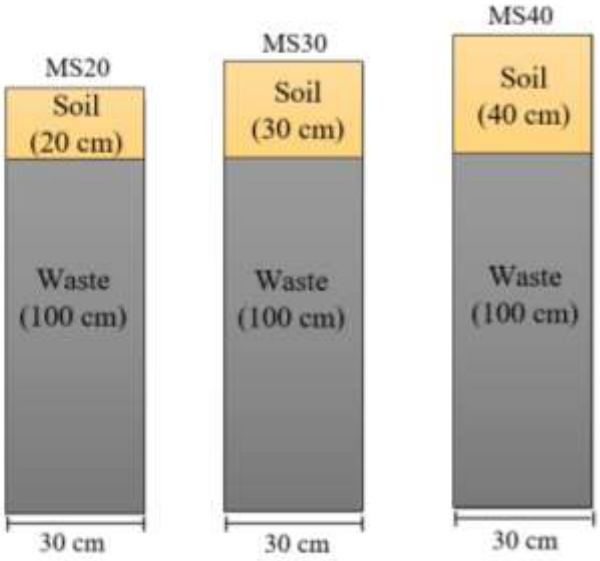


Figure 1 – Numerical models used.
Source: Authors (2024).

The soil input parameters used in the cover were obtained from characterization data of a cover soil from a landfill located in the metropolitan region of Fortaleza, whose geotechnical characterization was carried out by Elias (2018). The characterization of the material in the Unified Soil Classification System (SUCS) showed that it was clayey sand, demonstrating the predominance of sand particles (more permeable). Thus, it can be stated that the layer of material adopted does not efficiently meet the characteristics required for a typical dry cover system for a landfill. In Table 1 it is possible to observe the particle size distribution of the soil in the covering layer.

Table 1 – Particle size distribution of the soil in the covering layer.

Sample	Boulder (%)	Coarse sand (%)	Medium sand (%)	Fine Sand (%)	Silt (%)	Clay (%)
Cover layer soil	1	6	26	31	6	29

Source: Elias (2018).

According to USEPA (2004), ~~a~~ soil with suitable properties to be used in the covering layer of landfills must have a fines percentage between 30% and 50%. For CETESB (1993), the soil must contain more than 30% fine grain size in its composition. Thus, it can be stated that the selected soil has the granulometric characteristics required for use in the landfill cover layer.

The limits of liquidity (LL) and plasticity (LP) of the aforementioned covering soil are essential for understanding the behavior of the material. Cohesion and shear resistance are directly related to plasticity, which is associated with deformation. Therefore, Table 2 presents the classification according to the SUCS for the covering soil.

Table 2 – SUCS classification of the soil sample from the cover layer.

Sample	LL (%)	LP (%)	IP (%)	Granulometry	Symb. from the group	Name of the group
Cover layer soil	23.8	15.8	8	Fine soil	SC	Clay sand

Source: Elias (2018).

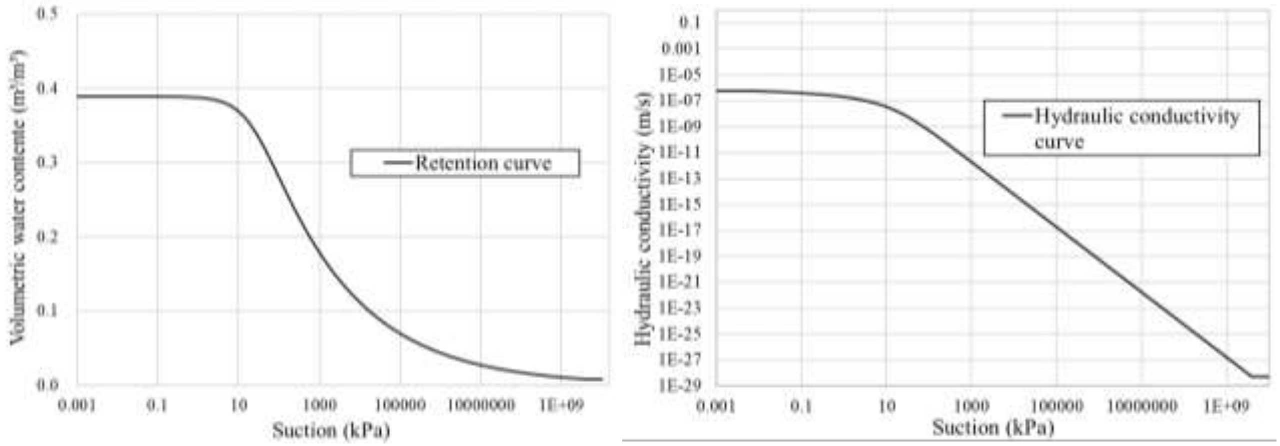
Compaction of the landfill soil returned values characteristic of a sandy clay and the average values obtained for optimal humidity (ωot) and maximum dry specific weight (ɣd) were 11% and 19.51 kN/m3, respectively.

Concerning MSW, the soil water characteristic curve and unsaturated hydraulic conductivity curve~~s~~ were obtained in the work of Breitmeyer et al. (2014), given the similarity of the geotechnical characteristics of the MSW tested by the authors and the MSW of the landfill in the metropolitan region of Fortaleza. For the covering soil, the retention and hydraulic conductivity curves were obtained in the study carried out by Souza (2018).

The finite element mesh used was the same for all models with square elements measuring 5 cm on each side, distributed equally over the entire geometry. Furthermore, it is important to simulate greater variations in the surface, so it was necessary to adopt three layers of surface elements, which are subject to climatic conditions, with 1 cm thickness each. It is worth noting that the refinement of the mesh was done through trials and this adopted configuration refers to the one that presented the smallest error in the water balance, as well as a good processing speed (Geo-Slope, 2007).

2.1 Input parameters

The relative input parameters used to feed the Vadose/w program were the soil water characteristic curve and unsaturated hydraulic conductivity curves of the natural soil and MSW. The Figures 2a and 2b present the soil water characteristic curve and unsaturated hydraulic conductivity curve~~s~~ obtained by Souza (2018), respectively.



(a) *(b)*

Figure 2 – Soil water characteristic curve (a) and unsaturated hydraulic conductivity curve (b) for natural soil. Source: Souza (2018).

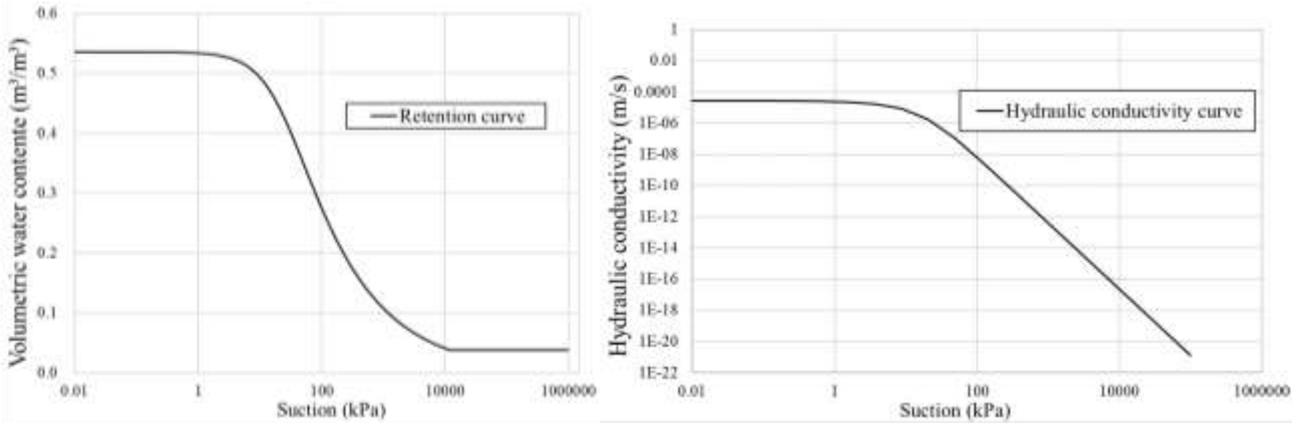
Analyzing the relationship between the volumetric water content and the unsaturated hydraulic conductivity with suction of the soil used as a cover, it can be seen that the hydraulic conductivity remains constant up to values close to the air entry value, defining the region in which the material is in a saturated state. For values greater than 10 kPa of suction, the clayey sand begins the desaturation process, moisture loss begins and the hydraulic conductivity value decreases.

From a certain suction value, materials that have a lower capacity to retain moisture may have lower hydraulic conductivities than thinner materials, which retain a greater volume of water. Therefore, not filling the voids creates air pockets that interrupt the flow channels, reducing conductivity.

To obtain the unsaturated hydraulic conductivity curve, Souza (2018) adjusted the data using the Van Genuchten method (1980), using the RETC software (Van Genuchten; Leij; Yates, 1991) from the experimental point obtained by the filter paper method. When adjusting the curves, the Non-Linear Regression Method was considered and the soil permeability coefficient (k_{sat}) was in the order of 6.70 x 10^{-7} m/s.

For Lambe and Whitman (1969), soils with a permeability coefficient (k_{sat}) between 10^{-7} cm/s and 10^{-5} cm/s are considered to have very low permeability. According to Daniel (1993), values of the order of 10^{-7} m/s are more appropriate, because the hydraulic conductivity of the soil would be lower. Thus, it appears that the soil applied to the landfill cover attends this criterion.

Regarding MSW, figures 3a and 3b present the retention and unsaturated hydraulic conductivity curves that were obtained by Breitmeyer et al. (2014) using non-linear regression, using a k_{sat} of 2.7x10^{-5} m/s.



(a) *(b)*

Figure 3 – Soil water characteristic curve (a) and unsaturated hydraulic conductivity curve (b) for MSW. Source: Breitmeyer et al. (2014).

Tropical soils are the most found in Brazil, they normally present curves with bimodal behavior, with two desaturation points and a characteristic plateau. The range of suction values for the climatic conditions of the metropolitan region of Fortaleza is generally from 0 kPa to $1x10^9$ kPa for the roof soil and 0 kPa to $1x10^6$ kPa for the MSW.

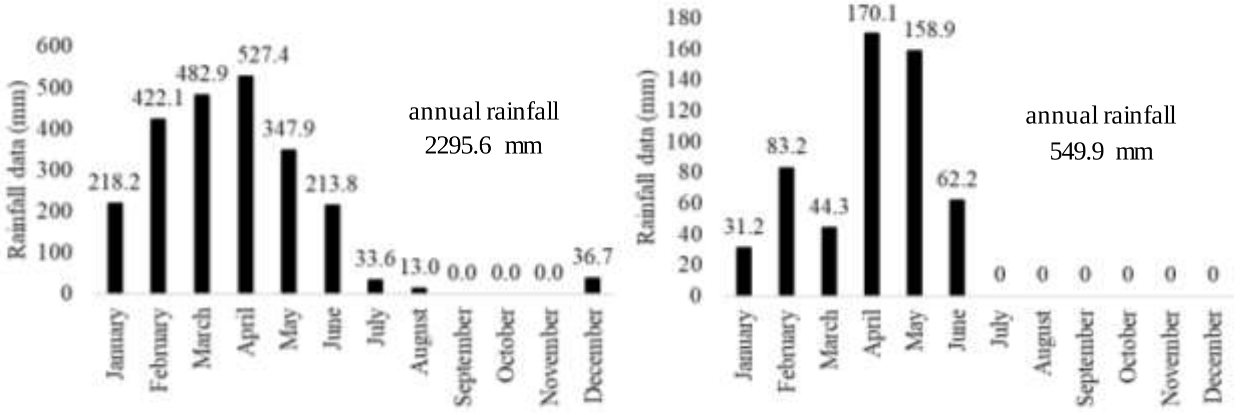
Concerning understanding the soil characteristic curve, there are two points to be analyzed, the first refers to the air inlet pressure, which represents the pressure differential between water and air necessary to cause drainage of the largest pore of the soil, and the second refers to the beginning of the residual stage of soil desaturation, in which the suction effect causes an additional loss of water. According to Alcântara (2007), the characteristic curve can help in estimating the maximum water retention capacity of the soil, which in turn, will influence the generation of leachate.

2.2 Boundary conditions

2.2.1. Climatic boundary condition

The boundary condition used on the upper face refers to climate data from a metropolitan region in the city of Fortaleza. In the lower boundary condition, a unit flow gradient condition was used.

Regarding climate data, precipitation values were selected from a period covering the years 2001 to 2021. The years in which the highest and lowest volumes of annual precipitation occurred during this period were the years 2019 and 2013, respectively, which presented annual volumes of 2295.6 mm and 549.9 mm. Figures 4a and 4b show the monthly rainfall for the years mentioned above. The data comes from the National Institute of Meteorology (INMET) portal, obtained through the monitoring system of an Automatic Surface Observation Meteorological Station (WMO Code: 81758), located 15.32 km from the study site.



(a) *(b)*

Figure 4 – Rainfall data from 2019 (a) and 2013 (b).
Source: Adapted from FUNCEME (2023).

The Penman Method (1948), modified by Wilson (1990), was used to estimate the real evaporation, which could be obtained through a routine available in the Vadose/w program. Data on maximum and minimum temperatures, wind speed, and relative humidity, obtained at a meteorological station in Fortaleza city, were used to feed the Vadose/w program that calculates real evaporation.

2.3.2. Initial condition

The modeling in the software was developed in two stages, the first stationary and the second transient. The initial condition was generated from transient modeling. To this end, an initial profile was determined with constant suction in the covering layer of -2.5 kPa and in the MSW of -20 kPa, with a temperature of 25°C used in an initial stationary analysis, these values are based on values from field measurements and were also used by Souza (2018).

From this first profile, a transient analysis was carried out using climatic conditions from the 2019 and 2013 precipitation averages, so that the final suction condition in the layers was equivalent to those at the beginning of the simulations. To do this, it was necessary to perform the transient analysis three times. Once this equilibrium profile was obtained, it served as the initial condition for the transient modeling of the years 2019 (higher rainfall) and 2013 (lower rainfall).

It is also noteworthy that the transient modeling was processed for each of the 365 days of the year with the highest and lowest annual precipitation (2019 and 2013) for the three models (MS20, MS30, and MS40). Regarding the modeling time interval, the time increment was adopted (time frames in which you want to visualize the results of 1 day).

3. Results and discussion

3.1. Hydric balance

The portions of the water balance that encompass a waste-cover system are precipitation, evaporation, surface runoff, and percolation of accumulated volume (m³). The Vadose/w program provides the results for each plot and an error associated with the numerical method and water storage. Tables 3 and 4 present the accumulated volumes of each portion of the water balance for the three models developed, considering the year with the highest and lowest rainfall, respectively.

Table 3 – Summary of the volumes of water balance components at the end of the year with the highest rainfall.

Parameters	**Model 1 (MS20+)**	**Model 2 (MS30+)**	**Model 3 (MS40+)**
Storage (m^3)	-0.0820	-0.0838	-0.0834
Error (m^3)	-0.0048	-0.0047	-0.0045
Evaporation (m^3)	-0.2500	-0.2449	-0.2435
Percolation	-0.5141	-0.4930	-0.4800
Precipitation (m^3)	0.6886	0.6886	0.6886
Surface runoff (m^3)	0.0113	0.0393	0.0531

Source: Authors (2024).

Table 4 – Summary of the volumes of water balance components at the end of the year with the lowest rainfall.

Parameters	**Model 1 (MS20-)**	**Model 2 (MS30-)**	**Model 3 (MS40-)**
Storage (m^3)	-0.0925	-0.0956	-0.0946
Error (m^3)	-0.0047	-0.0035	-0.0028
Evaporation (m^3)	-0.1824	-0.1726	-0.1691
Percolation	-0.0823	-0.0915	-0.0934
Precipitation (m^3)	0.1649	0.1649	0.1649
Surface runoff (m^3)	-0.0025	0.0000	0.0000

Source: Authors (2024).

According to Table 3, model 1 (MS20+) presented a lower surface runoff when compared to the volume of precipitation, denoting only 1.64% of the total volume of precipitation. At the end of that year, the percolated volume was 0.5141 m³, corresponding to 74.65% of the incident volume. There is also a significant loss due to evaporation, with an annual volume of 0.2500 m³, reducing the volume infiltrated into the roof.

Regarding model 2 (MS30+), surface runoff represented 5.7% of the total volume. Regarding percolation, at the end of 2019, the accumulated volume showed a reduction when compared to model 1, accounting for 71.59% of the volume. Evaporation was 0.2449 m³, that is, approximately 35.56% of the annual volume.

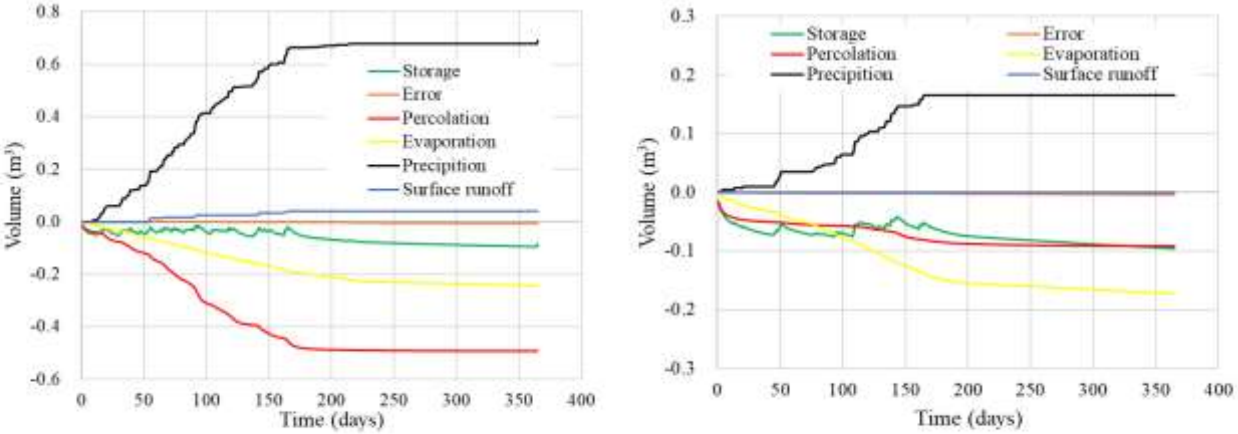
About model 3 (MS40+) the loss due to surface runoff was slightly higher than the previous models, denoting 7.71% of the incident volume, this, in turn, is caused by the thickness of the soil layer used being greater than the others, behaving as a natural barrier to water infiltration. Therefore, the hydraulic head total on the surface increases, leading to an increase in surface runoff during rainfall.

As for the percolation parameter, model 3 did not show any relevant variation, presenting an accumulated volume of 69.70%, inherent to 0.4800 m³. Evaporation was also significant, as were models 1 and 2. This fact reinforces the importance of studying the climatic factors in the region where the landfill is located, as mentioned by O'Kane et al. (2002). It is noteworthy that the parameter in question remained constant in all models analyzed, as well as the storage parameter. The error of all analyses in the three models was small and close, ensuring a greater degree of confidence in the results.

Based on Table 4, a deficit in surface runoff is observed for all models studied and significant evaporation, mainly for model 1 (MS20-). Regarding percolation and storage, the models did not present considerable differences, model 1 presented a lower annual percolated volume, which was 49.9%, while models 1 (MS20-) and 2 (MS30-) denoted a volume of 55.9% and 56.6%.

In general, the water balance parameters for the three proposed coverage models with thicknesses of 20, 30 and 40 cm for the year 2019 with the highest and for the year 2013 with the lowest rainfall did not show very significant differences. Considering the hydraulic performance criteria that a landfill cover must present, none of the models in the studied periods can be applied as a cover, due to the high percolation rates. Borghetti Soares et al. (2015) using the same software obtained good performance of the coverage system in their numerical modeling. The results showed good coverage performance, given the reduction in percolated volumes.

From this perspective, model 2 (MS30+) was defined to carry out the study of the water flow that occurs in the cover layer and the MSW, since it presents lower percolation and greater surface runoff than model 1 (MS20+) and values much higher similar to model 3 (MS40+). Furthermore, this model represents the coverage system applied to the landfill where the data originated. Figures 5a and 5b present the water balance plots of model 2 for the year with the highest and lowest rainfall, respectively.

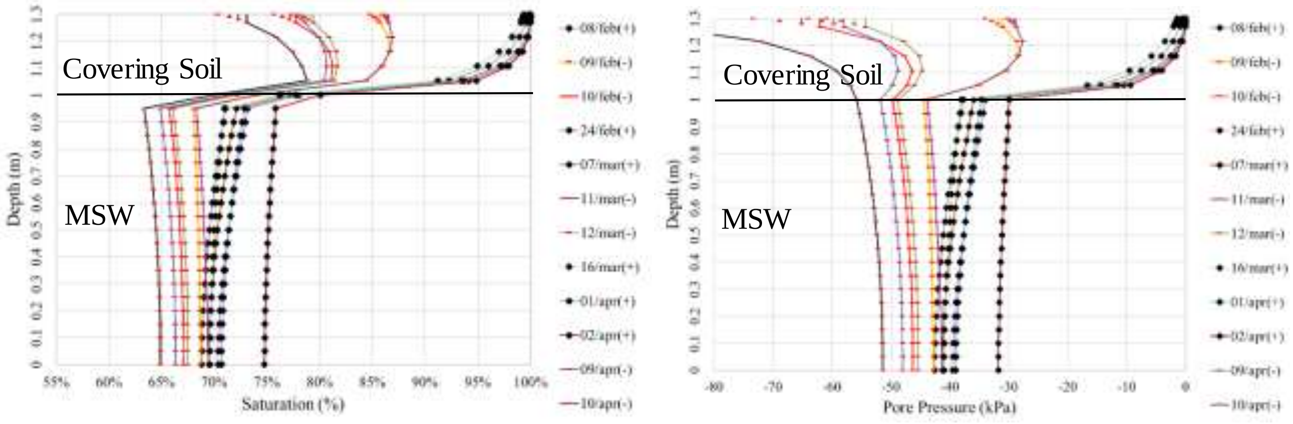


(a) *(b)*

Figure 5 – Water balance of the year with the highest (a) and lowest rainfall (b) in model 2.
Source: Authors (2024).

3.2. Water flux

This item presents the saturation and pore pressure profiles of Model 2 in the wettest quarter of 2019, the period with the highest rainfall in the historical series analyzed (February, March, and April). The same process was carried out for the quarter with the lowest rainfall volume of the year (2013), for October, November, and December. The saturation and pore pressure profiles of the two days with the highest volume (+) and lowest volume (-) of precipitation per month of the rainiest quarter, and two days of lowest precipitation per month of the least rainy quarter were selected, considering that in this quarter had no days with high rainfall. Figures 6 (a and b) and 7 (a and b) present the results provided by numerical modeling of water flow for the rainy and dry seasons, respectively.



(a) *(b)*

Figure 6 – Saturation (a) and pore pressure (b) profiles for the quarter of the year with the highest rainfall. Source: Authors (2024).

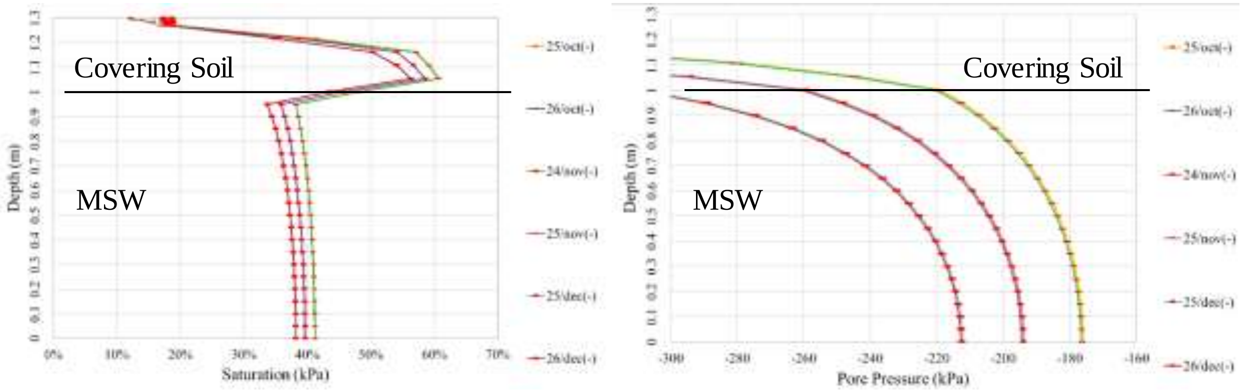
Considering the rainy season and the days with the highest rainfall per month, according to Figure 6a, it was observed that for the selected quarter, the aforementioned model presented a saturation of the natural soil layer with a variation of 75% at the beginning of the period and which reaches values of 100% when the heaviest rainfall occurs. It should be noted that the surface of the covering layer undergoes greater variations, considering that it is in direct contact with local atmospheric conditions. However, for the days with the highest rainfall in the quarter, the behavior is expected to be similar, as shown in the aforementioned saturation profile.

The saturation profile shows constant behavior in the MSW for each day that had the highest rainfall in the wettest quarter, with a variation between 68% and 75%. This reduction in saturation that occurs in the MSW, when compared to the saturation of the covering layer, is justified due to the latter being more exposed to greater rainfall and its main function, that is, to attenuate the entry of water into the waste as much as possible. At the MSW/cover layer interface, saturation presents similar values for days with high rainfall in the quarter, being approximately 73%.

According to Figure 6b, pore pressure varies from 40 kPa to 0 kPa in the cover layer, considering the days with the highest rainfall in the rainiest quarter. In MSW, pore pressure was constant, remaining around 43 kPa during these days.

Figure 6a also shows the analysis of the wettest quarter, considering the days with the lowest rainfall per month. For this condition, the model presented, for each day, profiles with a tendency to 70% saturation at the beginning of the cover layer, with high increases until approximately the first 10 cm, and then successive reductions until reaching the surface. Given this behavior, when comparing the saturation profiles of the days with the highest and lowest rainfall in the wettest quarter, it can be seen that even in the rainy season the layer does not maintain good saturation conditions for the situations considered, mainly in the vicinity of the surface where the greatest reductions occur, considering that it is in direct contact with local atmospheric conditions.

For days with lower rainfall in the rainiest quarter, the MSW presents constant saturation profiles for each day, with variations between 65% and 70% for the days considered. Regarding the covering layer, the pore pressure varies from 120 kPa to 50 kPa for the days with the lowest rainfall in the rainiest quarter. In the MSW, the average pore pressure of the days considered was 43 kPa, demonstrating constancy for each day.



(a) *(b)*

Figure 7 – Saturation (a) and pore pressure (b) profiles for the quarter of the year with the lowest rainfall.
Source: Authors (2024).

In relation to the dry season, in which there is no incidence of precipitation, it can be seen in Figure 7 (a) that the upper interface of the layer suffers a significant loss of saturation, reaching values of up to 12%, while the lower interface, close to to the MSW layer, maintains values, in a range of 40% to 50%. In the MSW layer, saturation showed an irrelevant variation, comprising constant values between 35% and 45% on the days analyzed.

According to Figure 7 (b), pore pressure reaches values above 220 kPa in the lower region of the soil layer. However, in the upper region, the pore pressure values for the days considered reach approximately 600,000 kPa, however, for better visualization, the profiles were plotted with pore pressure values of up to 300 kPa. For the MSW layer, pore pressures expressed values of up to 256,000 kPa.

Considering the absence of precipitation in the quarter, the flow inside the materials (soil and residue) showed a tendency towards an upward flow of desaturation. According to Souza (2018), this occurs due to the evaporation process on the surface of the roof, and consequently the decrease in saturation of the layers, being greater as it approaches the surface.

In general, it appears that the 30 cm layer of natural soil modeled with the aforementioned conditions does not have the capacity to maintain saturation levels in the dry season, being of utmost importance to reduce the flow of gases within the soil-MSW system. Therefore, the proposed soil-MSW system did not present considerable results, so its use is not recommended.

4. Final Considerations

In this work, numerical modeling of water flow was proposed to characterize the performance of the final cover of landfills of the MSW-soil cover type, using the Vadose/W software. The developed models were characterized in terms of geometry, initial conditions, boundary conditions and input parameters. The results obtained included the saturation and pore pressure profiles for the days with the highest and lowest rainfall in the rainiest quarter and for the days with the lowest rainfall in the least rainy quarter, considering the years with the highest and lowest rainfall volumes, namely 2019 and 2013, respectively.

According to the results obtained, the difference in the most significant parameters of the water balance of the analyzed models is small, however, all models developed showed high percolation rates. In this way, the model developed with a coverage of 30 cm of natural soil under the MSW layer was selected for the water flow analysis, considering that it was the configuration used in the landfill coverage system where the data were obtained.

The results obtained show that the selected model does not present good conditions for application in dry cover systems of landfills, considering that saturation conditions are not maintained during rainy seasons and dry seasons, which would allow the occurrence of exit of gas flow inside the system. Thus, the covering layer did not present a saturation greater than 85% in the wet and dry years, which according to Yanful (1993) it is the minimum percentage to guarantee an effective barrier against oxygen diffusion.

In short, numerical modeling proved to be a viable tool in estimating the water flow of MSW-soil cover type systems, helping to predict behavior, since its results allow the evaluation of its performance, without the need to produce an instrumented pilot cell in a landfill that is subjected to conditions similar to the best performing model (MS30), and measure all portions of the water balance, comparing with the numerical simulation. However, it is necessary to use parameters representative of the soil characteristics, in particular, Soil water characteristic curve curve and unsaturated hydraulic conductivity curve of the covering soil and MSW. In addition, boundary conditions (precipitation, wind speed, humidity, temperature, pressure) representative of the region to obtain a reliable coverage forecast.

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