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# A System Dynamic Model to Estimate Leachate and Biogas Production in MSW Irregular Disposal Areas Aided by Digital Terrain Model

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**Abstract:** Interactions between several parameters to estimate leachate and biogas production are very complex especially in irregular disposal areas without operational control and with few climate information. Nevertheless, the modeling challenges can be overcome using a System Dynamics (SD) approach that allows measure long term dynamics of a complex system. The proposed model is based upon a computer simulation to understand circular causality among soil water balance model and modified first-order decay methane generation aided by MSW landfilled volume calculation from Digital Terrain Model. The leachate accumulated is considered as targets for the calibration and validation. A model test run demonstrated that measured and calculated values of the leachate flow rate, applied in Volta Redonda's uncontrolled landfill (Brazil) with a spatial resolution of 4,3 cm, were similar (RMSE = 0.10013 and SD = 0.0994). The SD model fitted with higher accuracy with the real data, indicating differences less than 8% for leachate production. After landfill methane generation parameters translating among first-order decay model it was found k = 0.28 1/yr and the $L_0$ = 62,18 ($m^3$ $CH_4$/ton waste). The obtained result were compared to the LandGEM modified model results and shows that the proposed method was capable of predicting the final productivity without overestimating the methane yield and was also able to capture the system behavior.

**Keywords:** MSW Irregular Disposal Areas, System Dynamics, Remote Sensing, Simulation, Leachate, Biogas

## 1. Introduction

The Municipal Solid Waste (MSW) disposal trends in developing countries in the last decade showed a modest increase in engineered landfills use regardless of overall progress such as the MSW collection service growth. Nonetheless, proper management still a challenging task due to poor operating conditions, lack of budget, and inappropriate standards [1, 2]. Particularly in Brazil, the final disposal in sanitary landfills increased by 2,7% between 2010 – 2019 and the collection service available for the population increased from 88% to 92%, as well as the quantity of MSW landfilled in irregular areas - uncontrolled landfills and dumpsites (2010: 25 x $10^6$ tons; 2019: 29 x $10^6$ tons) [3]. Constructed sanitary landfills and uncontrolled facilities are the main options of MSW disposal which are accompanied by leachate and gas generation, which represents significant potential sources of pollution/contamination and public health concern [4-6].

Despite the lowly increase of waste being composted, reused or recycled, organic materials waste, paper, and paperboard waste represent the largest proportion of the waste stream in Brazil (2019: 55,7%). One of the most important impacts on the environment derived from landfilled organic content is the biogas production via anaerobic systems [3, 7].

A global effort to assist poor and developing countries to close their dumpsites has been developed by International Solid Waste Association (ISWA) and United Nations Environment Programme (UNEP), however, the multi-actor participation to change the reality is complex [8, 9]. In Brazil, the waste management policy that has been implemented (Brazilian Solid Waste Policy – PNRS, Law nº. 12305/2010) failed to accomplish the imposed requirements.

The PNRS outlawed the irregular disposal practice after August 2014, but the goal was not achieved and a new sanitation policy was established in 2020 - Law nº 14026/2020 - extend the deadline for 2024 according to population size [10, 11].

There are a high number of open dumpsites in Brazil (3326 sites) without proper containment systems mainly due to ineffective environmental legislation application [4]. A properly decommissioned project has high costs and complexity and needs to undertake in a planned and effective manner, however in Brazil the designed project for MSW irregular disposal adequation is performed only with geometric reconfiguration, MSW final covering with soil, and an attempt to drainage the leachate [12-14].

To correctly design treatment systems, a model that represents a highly complex system (high temporal and spatial variability) is critically needed. Furthermore, the dynamic properties in the processes of methane and leachate production cannot be fully characterized by traditional forecasting methods, often considered a challenge [15]. These effluents are related to several factors, including climate and waste landfilled data, site design conditions, final cover layer characteristics, biochemical reactions, moisture content, temperature, and gravimetric composition. The several factors and the high variations in static models lead to complex modeling processes which are expressions of a trend that verifying the inherent systematic features [16-18]. An alternative to this is a dynamic modeling approach that handles forecasting issues under uncertainty and data scarcity. Dynamic interactions analysis and dynamic modeling are extremely important to understand the dynamic interrelationships among all aspects and elements of methane/leachate generation in uncontrolled disposal areas with no database. It is of special significance the role of information feedback and system behavior to address issues associated with the growth of Greenhouse Gas (GHG), leachate contamination and site management [19-22].

The SD approach could combine the modified first-order decay system, the adapted water balance method, and the waste quantity data scarcity by accounting the interrelationships among relevant features for developing a simple and yet realistic model for methane/leachate generation [23, 24].

Other challenges are the real surface area and the waste volume landfilled determinations. To overcome these issues, it is possible to use Unmanned Aerial Vehicles (UAV) system and their processing platforms for generating a Digital Terrain Model (DTM) and calculating the bulk volume. A DTM is represented as a three-dimensional (3D) raster image that shows the elevations of ground above the mean sea level or above a vertical datum. The UAV- processing platforms methodology, undoubtedly, provides better results than the traditional methods and also requires less time and costs [25-28].

Despite the great complexity of the processes, the wastes heterogeneous mass, a large number of variables, and the data scarcity the SD approach is able to model saturated and unsaturated hydraulic conductivity, leachate and biogas flow rate, the first-order reaction rate (k), and specific methane volume produced ($L_0$) in uncontrolled landfills in humid regions, constituting a reliable and cost-effective tool that direct help remediation strategies of old dumping sites.

## 2. Materials and Methods

A two-stage time series model was performed using five categories of data: landfilled waste volume, the site geometric definition, climatological data, hydrological processes in soil–waste–atmosphere continuum, and waste gravimetric composition.

### *2.1. Digital Terrain Model Development*

UAV was used for mapping the survey area and was equipped with a global positioning system and a digital camera. The flight was carried out with an autopilot using the Mission Planner software at an altitude of 119,95 m, which yielded a Ground Sample Distance (GSD) of 0.43 cm with numbers of captured images of 246 (forward overlap and side overlap set to 80% and 60%, respectively). Were signalized 13 Ground Control Points (GCPs) using GNSS-RTK (Real-Time Processing) model to aid the Agisoft software to reduce the maximum horizontal and vertical Root Mean Square Error (RMSE) and to improve the accuracy of triangulation. GCP was measured with Global Navigation Satellite System Technology – GNSS (total station base GNSS), with a Hi-Target V30 L1 / L2 GNSS, and Hi-Target GNSS receiver V30 L1 / L2 - (total station rover GNSS). The photogrammetric products were processed using Agisoft PhotoScan and ArcGIS for Desktop 10.2. This software were set to obtain the highest 3D point cloud density, Digital Terrain Model (DTM), orthomosaics and slope variation [29-31]. The ArcGIS software workflow begins with importing GCP, level curves, and the altitude points with the associated information as well as all the other elements that are important for the terrain mathematical modeling. This information allowed the DTM creation using a set of elevation marks at the nodes of a Triangular Irregular Network (TIN) [32]. As the DTM is built the software allows the volume, real surface area, and a local slope measurements [28].

### *2.2. SD Model Development*

A schematic diagram reproducing the climate processes in the soil surface, water movement in the cover layer, moisture interaction in the MSW, transformations underwent by the organic matter as a consequence of the biodegradation process, and released gases, is shown in Figure 1 [33].

Landfill water balance was derived from primary sources, such as: (i) waste moisture content; (ii) precipitation; (iii) leachate; (iv) evapotranspiration; (v); water consumption in biodegradation process and (vi) water lost as water vapor. STELLA model development is based on the processes presented in Figure 1 and detailed SD model construction steps are given below.

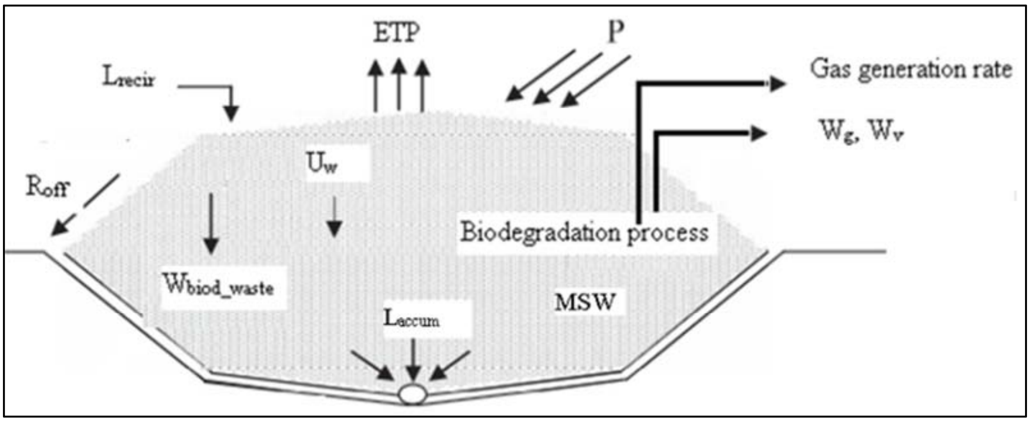



***Figure 1.*** *Biogas/leachate production conceptual model.*

The adapted equation employed for leachate flow rate is given as [34]:

$$L = [A \times ((P — R_{off} — \Delta Sw — ETR)/1000))] — W_g — W_v + W_{waste} — VFC_{waste} + L_{recir} \quad (1)$$

Where L is the leachate flow rate ($m^3$/year); A is the real surface área ($m^2$); P is the Precipitation (mm/year); $R_{off}$ is the surface runoff (mm/year); ΔSw is the change in water storage in the soil (mm/year); ETR is the Real Evapotranspiration (mm/year); $W_g$ is the water consumed in biogas formation ($m^3$/year); $W_v$ is the water lost as vapor during biogas formation ($m^3$/year); $W_{waste}$ is the moisture content of the waste ($m^3$/year); $VFC_{waste}$ is the water volume at waste field capacity ($m^3$/year); $L_{recir}$ is the leachate recirculation ($m^3$/year); 1/1000 = conversion factor.

### *2.3. Data Generation Overview*

The SD model requires: two climate data (normal mean monthly precipitations and normal mean monthly temperatures) for computing Real Evapotranspiration; soil characteristics (sand content, silt content, clay content, organic carbon content, bulk density and particle density); design specifications (mean slope) and MSW gravimetric composition to realize the simulation.

The soil surface is considered saturated keeping the same water content before precipitation. This consideration is valid as moisture advances (z1 = h1, z2 = h2) and the capillary tension remains the same at any position and time in wetting front. The saturated hydraulic conductivity is obtained from soil physical-chemical properties. The SD model assumes Darcian flow for vertical drainage (the net water lateral drainage, Ron = 0), and it is limited by the saturated hydraulic conductivity and available water soil storage. If the soil water content is greater than field capacity the percolation is computed as [35]:

$$D_{percolation} = k_{sat} \times (\theta_{soil} — FC) \quad (2)$$

Where $D_{percolation}$ is the deep percolation rate ($cm^3$/s), $k_{sat}$ is the saturated hydraulic conductivity ($cm^3$/s), $\theta_{soil}$ is the volumetric soil water content ($cm^3/cm^3$), and FC is the field capacity ($cm^3/cm^3$).

The soil water content is equal to soil water divided by total soil volume. If the soil water content is less than field capacity the vertical drainage rate out of soil use unsaturated hydraulic conductivity estimated by the following equation [36, 37].

$$k_{uns} = k_{sat} \times [(\theta_{soil} — \theta_{residual})/(\Phi — \theta_{residual})]^{3+(2/\lambda)} \quad (3)$$

Where $k_{uns}$ is the unsaturated hydraulic conductivity ($cm^3$ /s), $\theta_{residual}$ is the residual volumetric soil water content ($cm^3/cm^3$), Φ is the porosity (dimensionless) and λ is the pore-size distribution index (dimensionless).

The unsaturated soil water content that changes over time is calculated through water characteristic curve and van Genuchten model is one of the most frequently used [38]:

$$Se = (\theta_{soil} — \theta_{residual})/(\theta_{sat} — \theta_{residual}) = [(1+|\alpha \times \varphi|^n)]^{-m} \quad (4)$$

Where Se is the effective degree of saturation (dimensionless), $\theta_{sat}$ is the saturated soil water content ($m^3/m^3$), φ is pressure (cm), and α, n, and m are empirical parameters. The parameter m is expressed as m = 1 — (1/ n).

The simulation is performed assuming the following questions: transpiration from cropped soil is zero; the water entering the landfill from aquifers and the water produced due to waste biodegradation are negligible; water consumed in biodegradation process and water vapor that leaving with biogas are estimated in biodegradation module; the water content in the waste that generates leachate is greater than MSW field capacity estimated by (5) [39].

$$VFC_{MSW} = \theta_{MSW} \times [(\gamma_{MSW} \times Area \times S)/(V_{MSW} + D_{percolation})] \quad (5)$$

Where, Sw is the soil water storage (m/m), $\gamma_{MSW}$ = specific weight of waste (0,7 ton x $m^{-3}$) [40], $V_{MSW}$ is the MSW volume landfilled ($m^3$) and Area is the superficial area ($m^2$).

Due to the lack of some meteorological data, Potential Evapotranspiration (ETP) was calculated using modified Thornthwaite and Mather method [41-43]:

$$ETP = [16 \times ((10 \times T_n)/I)^a] \times (N \times ND)/360 \quad (6)$$

$$I = \sum_{n=1}^{12}(0,2 \times T_n)^{1.514} \quad (7)$$

$$a = (6.75/10^7) \times I^3 - (7.71/10^5) \times I^2 + (1.7912/100) \times I + 0.49239 \quad (8)$$

Where ETP is the Potential Evapotranspiration based on a 12-hour day and 30-day month (mm x $month^{-1}$), $T_n$ is the monthly mean air temperature (°C), I is the heat index for the station which depends upon long period mean monthly air temperatures, a is the regional thermal index dependent on I. ETP is corrected by actual day length in hours, h, and days in a month, N. N is the astronomical day expressed in 12 h units of a 30-day month at a latitude where ETP is to be calculated, ND is the number of days;

ETR is calculated by setting a condition: if P — ETP < 0 → ETR = P + | ΔSW | (ΔSW is the change in soil water storage) [44, 45]:

$$\Delta SW_i = (S_i - S_{i-1}) \quad (9)$$

$$S_{final,i} = S_{i-1} \times e^{[(P-ETP)i/Ssoil]} \quad (10)$$

Where $\Delta S_i$ is the soil water storage change between the periods i and (i — 1) (mm/m), S is the soil water storage (mm/m).

Otherwise: $P - ET_P > 0$, the soil water storage is estimated by:

$$S_{final,i} = S_{i-1} + (P - ETP)_i \quad (11)$$

The ETP calculations start when final water storage is greater than soil water storage represented as following:

$$S_{final,\ initial\ month} = [\sum(P - ETP)_{positive\ values}]/[1 - e^{(P-ETP)negative\ values/Ssoil)}] \quad (12)$$

Field capacity (FC) and permanent wilting point (WP) are used to predict the total available soil water (TAW) and to predict saturated soil moisture content, residual soil moisture content, pore size distribution index, van Genuchten parameter (α) and pedotransfer functions are used with soil hydraulic behavior via the van Genuchten model as following [46-51]:

$$FC = 0.1535 - (0.0018 \times Sand) + (0.0039 \times Clay) + (0.1943 \times \Phi) \quad (13)$$

$$WP = 0.037 - (0.0004 \times Sand) + (0.0044 \times Clay) + (0.0482 \times \Phi) \quad (14)$$

$$S_{soil} = TAW \times L \quad (15)$$

Where FC is the field capacity ($m^3/m^3$), WP is the permanent wilting point ($m^3/m^3$), Φ is the porosity (dimensionless), Sand is the sand content (%), Clay is the clay content (%), L is the soil layer thickness (m) and TAW is the total available soil water (mm);

$$\theta_{sat} = (0.81 - 0.283 \times \gamma_{bulk} + 0.001 \times Clay) \times (Saturation\ parameter) \quad (16)$$

$$\theta_r = 0.014 + (0.25 \times WP);\ WP \geq 0.04 \quad (17)$$

$$\theta_r = 0.6 \times WP;\ WP < 0.04 \quad (18)$$

$$\lambda = \exp(0.78+0.0176\times Sand-1.06\times\Phi-0.000053\times Sand^2-0.00273\times Clay^2+1.11\times\Phi^2-0.0309\times Sand\times\Phi+0.000266 x sand^2\times\Phi^2-0.00611\times Clay^2\times\Phi^2-0.00000235\times Sand\times Clay+0.00799\times Clay^2\times\Phi-0.00674\times\Phi^2\times Clay) \quad (19)$$

$$\alpha = \exp(-2.486+0.025 x Sand-0.352 x C-2.617 x \gamma_{particle}-0.023 x Clay) \quad (20)$$

Where λ is the pore-size index (dimensionless), $\gamma_{particle}$ is the particle density (ton x $m^{-3}$), $\gamma_{bulk}$ is the bulk density, C is the organic carbon content (%) and Saturation parameter = 0,9 for clay soil (dimensionless).

The relation between ETP with the maximum amount of water available for evaporation allows ETR calculation. If ETP is greater than water stored at superficial soil layer, only the accumulated amount will evaporate. The surface runoff ($R_{off}$) was obtained from tables that take into account the soil type and its slope (slope map drew as a map based on the current surface - MDT), in addition to precipitation data computed as [33, 41]:

$$Roff = P \times C \times \alpha \quad (21)$$

Where $R_{off}$ is the surface runoff (mm), C is the surface runoff coefficient depending on the characteristics of vegetation, topography and soil (dimensionless) and α is the empirical parameter depending on the seasons (dimensionless).

The water consumption and the MSW organic matter methane generation ($C_m$) are depending on the waste gravimetric composition (waste biodegradable fraction – $BF_w$) according to stoichiometric equation based on the atomic composition of the waste material by taking into account the elements C, O, H, N and ammonia. The model requires waste composition expressed as percentage weights of waste fractions (organic, paper, cardboard, glass, etc.) as input $BF_i$ values (dry basis) [52].

$$C_nH_aO_bN_c+[n-(a/4)-(b/2)+(3xc/4)\ H_2O \rightarrow [(n/2)-(a/8)+(b/4)-(3xc/8)]CH_4+[(n/2)-(a/8)+(b/4)+(3xc/8)]CO_2+cNH_3 \quad (22)$$

$$BF_{total} = \sum_{i=1}^{n} BF_i \times FR_i \quad (23)$$

$$C_m = (\sum_{i=1}^{n} BF_i \times FR_i \times C_{mi})/(BF_{total}) \quad (24)$$

Where $C_aH_bO_cN_d$ is the empirical elemental composition of the organic material at the beginning of the process, n is the moles of organic matter in the output/moles of organic matter in the input, $FR_i$ is the fraction of each component in the waste composition; $Cm_i$ is the MSW organic matter methane generation for type of waste components ($m^3$ $CH_4$/dry-ton).

The water content, w, is calculated by dry mass of potentially Degradable Organic Matter (DOC):

$$w = [(BF_w \times C_m)/L_0] — 1 \quad (25)$$

Where w is the water content (kg $H_2O$/dry-kg bulk waste) and $L_0$ is the methane generation potential ($m^3$ $CH_4$ /waste ton).

Several methods based on simulation models (biogas production mathematical models) or on measurement methods exist for the estimation of Landfill Gas (LFG), nonetheless, the largely used model is the Landfill Gas Emissions Model -LandGEM-, and all models use the same fundamental First-Order Decay (FOD) equation. LFG is a product of organic waste decomposition processes that consider methane emission decreasing and exponential over time and the knowledge of the degradable organic carbon (DOC), methane generation potential ($L_0$), and the methane generation rate (k) could be helpful for the biogas prediction [18, 53-55].

The methane generation was modeled (biodegradation module) as a function of each waste component using IPCC equations [56, 57]. The translation of DOC to $L_0$ using other parameters in the IPCC model incorporated a large degree of uncertainty therefore more accurate predictions using multiple waste components and "multiphase" models (calculations for each component in parallel and summing the results to predict the total) have been applied with unique $L_0$ and k values for SD model.

$$Q_{T,x \text{ before closure}} = {}_x\sum^t\{[A \times k \times Mi \times L0) \times (1— e^{-kt})]—Rx\} \times (1—OX) \quad (26)$$

$$Q_{T,x \text{ after closure}} = {}_x\sum^t\{[A \times k \times Mi \times L0) \times (e^{-kx} — e^{-kt})]—Rx\} \times (1—OX) \quad (27)$$

Where (before landfill closure) $Q_{T,x \text{ before closure}}$ is the methane generated in the current year T ($m^3$/year), t is the year of inventory, x is the years for which input data should be added, $A = (1 – e^{-k})/k$ is the normalization factor which corrects the summation, $M_i$ is the total Municipal Solid Waste (MSW) generated in year x (ton/year), $R_x$ is the recovered $CH_4$ ($m^3$/year) (adopted value = 0) and OX is the oxidation factor (adopted value= 0).

After closure: $Q_{T,x \text{ after closure}}$ is the methane generated in the current year T ($m^3$/year).

The biodegradation module incorporates a multiphase model with a single, weighted-average waste stream translated for input into a single-phase model. The SD model can be used with site-specific data as total MSW landfilled ($M_i$ – volume calculation by DTM), methane generation potential ($L_0$), degradable organic carbon (DOC), a fraction of DOC dissimilated ($DOC_f$), the decay rate of waste (k), and Methane Correction Factor (MCF) optimized for developing country's default parameters for the emission inventory, by the following equations [58, 59].

$$L_{0j} = MCF \times DOC_j \times DOC_{f,j} \times F \times (16/12) \quad (28)$$

$$DOC_j = (\sum DOC_i \times M_i)/ \sum M_i \quad (29)$$

$$DOC_{f,j} = (\sum DOC_{f,i} \times M_i \times DOC_i)/ (\sum DOC_{i} \times M_i) \quad (30)$$

$$K_{c,j}=(\sum DOC_{f,i}xM_ixDOC_ixk_i)/(\sum DOC_ixDOC_{f,i}xM_i) \quad (31)$$

Where $M_i$ is the waste mass of component i in year j (ton), j is the year in which waste is landfilled, $DOC_i$ is the degradable organic carbon concentration of waste component i (ton C x ton$^{-1}$ waste), $DOC_{f,i}$ is the fraction of $DOC_i$ that will anaerobically degrade in component i, $k_{c,j}$ is the methane generation rate calculated by weight of carbon in waste in year j ($yr^{-1}$).

The chemical reaction for water lost as vapor during biogas formation is calculated according to ideal gas law.

### *2.4. System Dynamic Model*

System Dynamics (SD) is a methodology based on feedback principle that interconnected information between the various components that affect fixed quantities of the system over time and handle easily the non-linearity and counterintuitiveness (cause and effect are distant in time and space), time-delay and the multi-loop structures of the complex and dynamic systems providing a simple solution to complex nonlinear problems [60-62].

Feedback mechanisms are represented by closed-loop systems and cover any process that the inputs are changed based on output [35]. For example, the generation solid waste growth represents a positive feedback system: solid waste generation increase with growing population. On the other side, the composting waste growths represent a negative feedback system: the composted waste increase reduces the remaining portion of the organic fraction landfilled which leads to reduction of GHG emissions.

The conceptual model is constructed with building blocks (variables) categorized as: stocks (symbolized by rectangles), flows (symbolized by valves), converters (symbolized by circles), and connectors (symbolized by arrows). In this research, the system dynamics modeling were developed using the system dynamic tool STELLA software package that is able to develop a SD model by assigning the appropriate values and functions to the system [63, 64].

## 3. Results and Discussion

All measurements performed from UAV image service (adjusted image with the georeferenced GCP with GNSS - orthophoto) comprised of a DTM - Figure 2 – can be seen in Table 1.

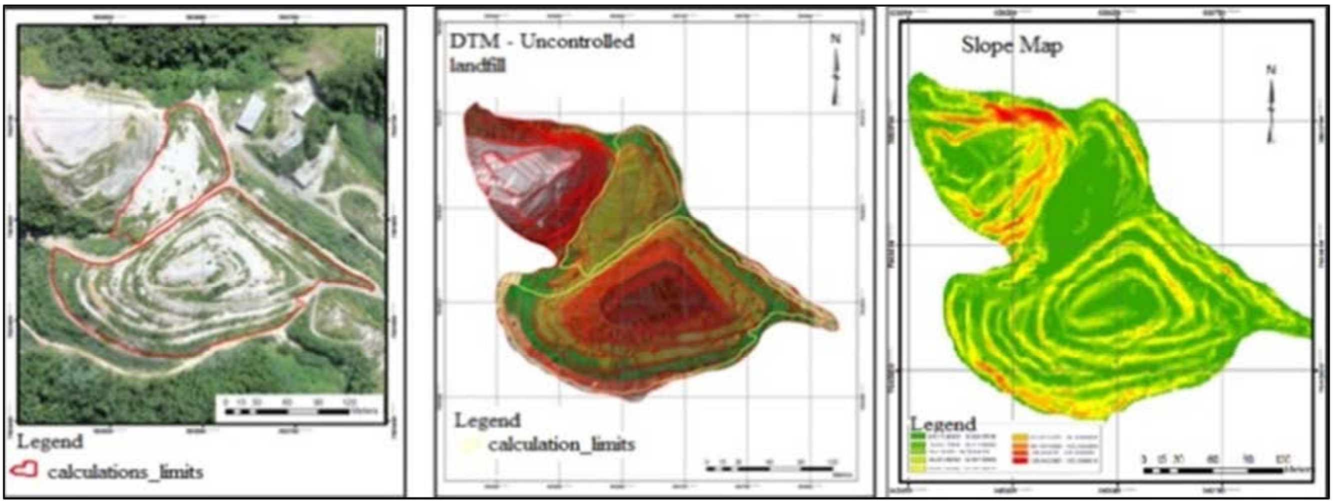



***Figure 2.*** *Orthophoto (left), DTM, and Slope Map (right): Volta Redonda RJ – Brazil.*

The MSW volume landfilled based on 246 images with 13 GCP was calculated after field data determination with the UAV and GNSS. The data was saved in ".shp" format for reading on ArcGIS, and subsequently converted into a TIN surface using the tool "Create TIN" from which can be calculate the volume.

***Table 1.*** *Volume, area, and perimeter obtained from UAV image service processing.*

| | Area ($m^2$) | Perimeter (m) | Volume ($m^3$) | Mean slope (%) |
|---|---|---|---|---|
| Area 1 | 7739,73 | 393,9 | 47419,11 | |
| Area 2 | 29031,23 | 789,33 | 488336,68 | 2 |
| Total | 36770,96 | 1183,23 | 535755,79 | |

The images taken from a photographic camera with GPS coupled to UAV were processed in Agisoft Photoscan software. The Photoscan software optimizes the camera parameters and points feature automatically. The distance between the two coordinate (GPS and total station) calculated based on the measured coordinates was evaluated by means of the Root Mean Square Error (RMSE) as to accuracy measure, using 13 checkpoints (GCP) [65].

$$RMSE = \sqrt{(\sum \Delta h^2)/n} \qquad (32)$$

Where $\Delta h$ is the difference between X, Y, and Z coordinates of the ith GCP measured with RTK-GNSS and X, Y, Z coordinates of the ith GCP as from the identification in the images measure with GPS and n is the total number of GCPs.

The calculated values show that the $RMSE_X$ = 0,07287 meters, $RMSE_Y$ = 0,041791 meters, $RMSE_Z$ = 0,232317 meters are greatly smaller when GCPs are used to adjust the images coordinates (linear measure - meters). DTM accuracy is directly proportional to the RMSE values.

The Decree 89817/1984 constitutes a regulative instrument to evaluate cartographic product positional accuracy in Brazil and Table 2 indicates the accuracy standards for this survey [66].

***Table 2.*** *Brazilian map accuracy standards (Act n° 89.817/84).*

| Brazilian Accuracy Standards | 1:1000 Error | RMSE X,Y, Z Error (m) |
|---|---|---|
| Class A | 0,17 m | X: 0,072 – Approved; Y: 0,041 - Approved |
| Class B | 0,30 m | Z: 0,23 - Approved |
| Class C | 0,50 m | - |
| Class D | 0,60 m | - |

The evaluation of the 3D positional accuracy presented Class A for planimetric (X, Y) accuracy and Class B for altimetric (Z) accuracy at 1:400 scale according to the methodology of Decree 89817/1984 that indicates the high accuracy of the coordinates e respectively of the DTM.

After understanding the conceptual processes described in Figure 1 and identifying the primary functions, a SD model is created (Figure 3) and the model equations will be generated by the STELLA software (Figure 4). The biodegradation module was development separated and is shown in Figure 5.

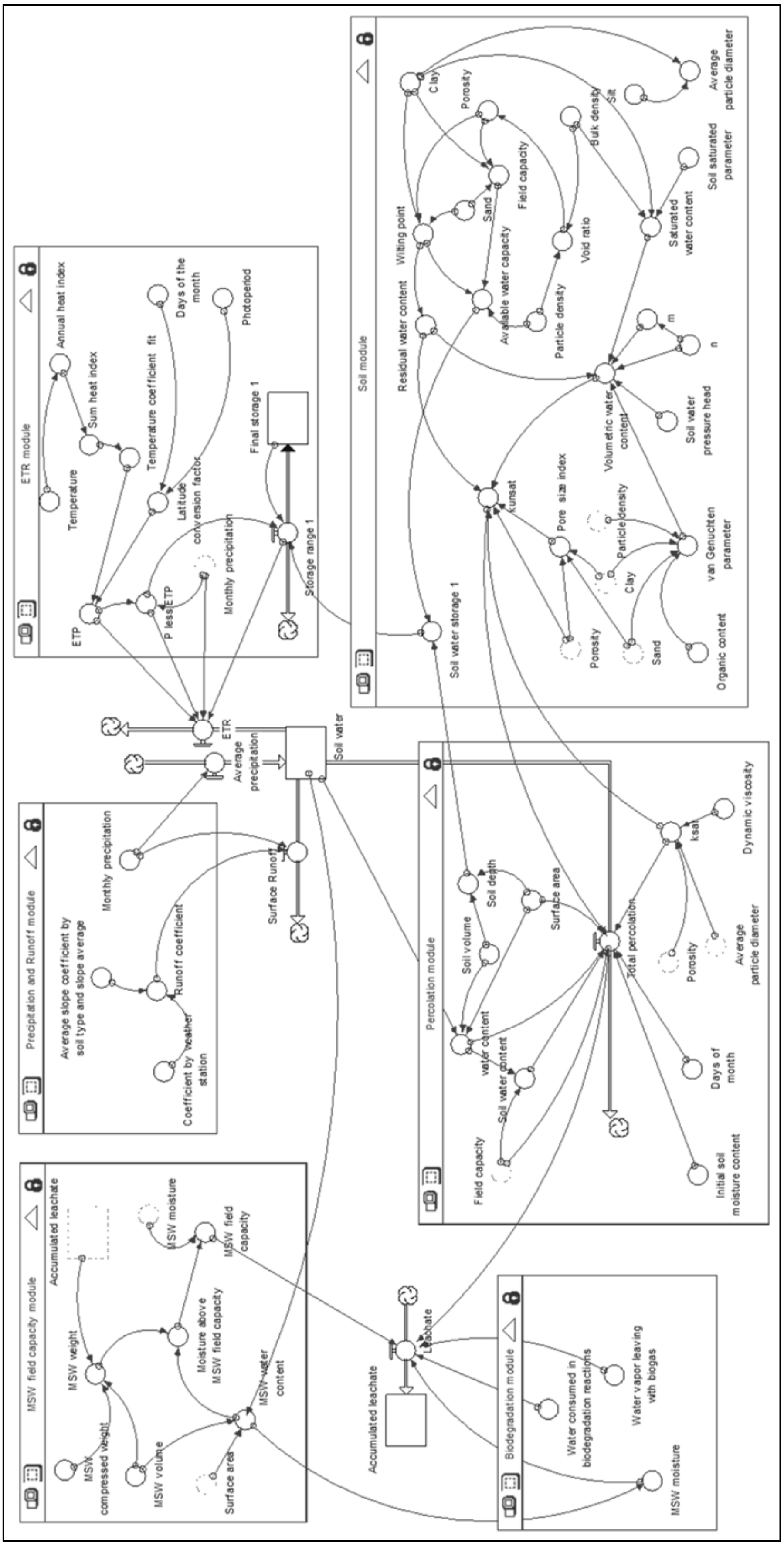
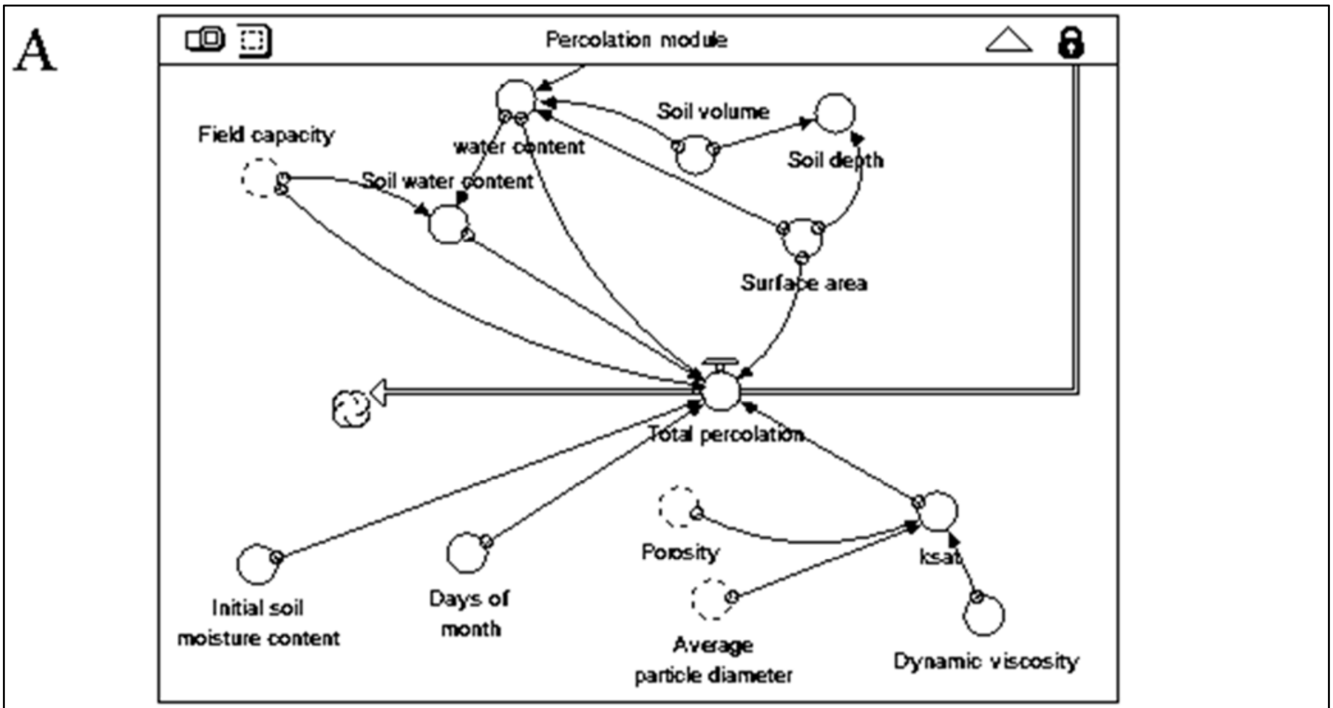



***Figure 3.*** *A SD model with STELLA for simulating leachate production.*

Some considerations can be pointed out, for example, the percolation rate through superficial soil into MSW profile described by (2) can be converted into a SD model component as shown in Figure 4.




**B**

**Percolation module**

```
Total_percolation = IF(water_content>Field_capacity) then
((ksat*864*Days_of__month)*(Initial_soil__moisture_content-Soil_water_content)*Surface_area)
ELSE
((kunsat*864*Days_of__month)*(Initial_soil__moisture_content-Soil_water_content)*Surface_ar
ea)
water_content = (Surface_area*Soil_water)/(1000*Soil_volume)
Soil_water_content = IF(water_content>Field_capacity) then water_content ELSE Field_capacity
ksat =
((981/Dynamic_viscosity)*((Average__particle_diameter^2)/18000)*((Porosity^3/(1-Porosity)^2)))/1
00
```

***Figure 4.*** *(A) A diagram showing percolation module with STELLA; (B) associated program code (B).*

The rectangles (Figure 3) represents soil Final Storage 1 (only for ETR calculation), Soil Water storage for total percolation calculation and accumulated leachate. The double lines represents the following rates: average precipitation, ETR, surface runoff, leachate, soil Storage Range 1 (only for ETR calculation) and the water that percolates into the soil and waste profile.

The other variables represented by circles (Figure 4A) denote the $k_{uns}$ (soil module), surface area, soil depth, soil volume, water content (volumetric water content), soil water content (volumetric soil water content), field capacity, $k_{sat}$, dynamic viscosity, soil porosity, average particle diameter, numbers of days of month and initial soil moisture content (initial volumetric soil water content). These circles in Figure 4A are linked through single lines used to calculate total percolation, water content (volumetric water content), soil water content and $k_{sat}$.

In Figure 4B, if the water content is greater than field capacity, then the total percolation can be estimated by (2) multiplying by superficial area, whereas the water content (volumetric water content) is obtained by dividing the soil water multiplying surface area with soil volume. If water content is less than field capacity, then the total percolation can be estimated by (2) using unsaturated hydraulic conductivity. The SD model present two options to calculate $k_{uns}$: by water characteristic curve and soil water potential taking the advantage of the STELLA software or by (3) and (4).

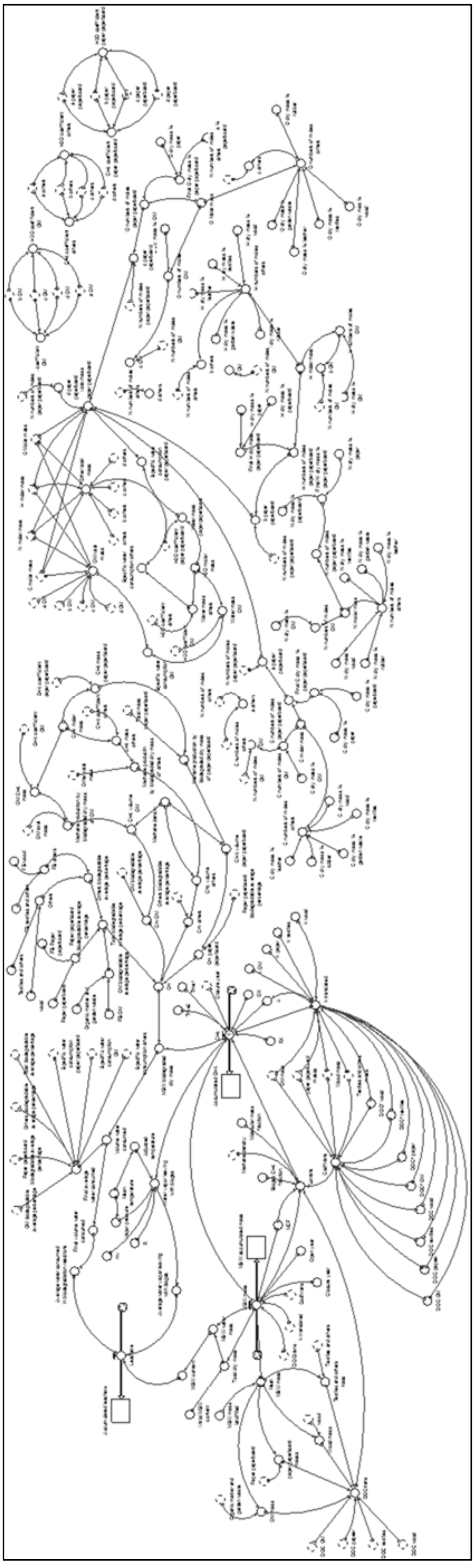
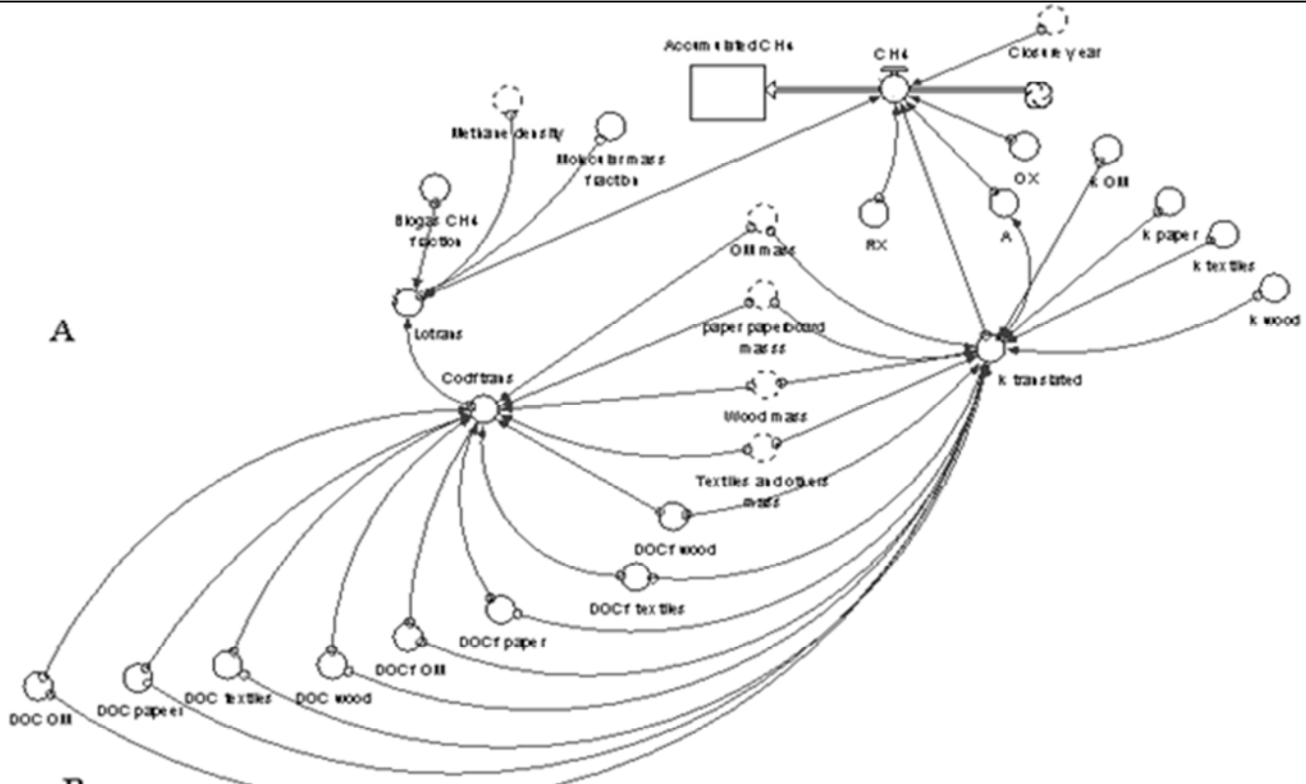


***Figure 5.*** *Biodegradation SD model – biodegradation module.*

The connectors in Figure 5 are used to calculate methane flow rate, average water consumed in biodegradations reactions and average water vapor leaving with biogas – Biodegradation Module. All variables (e.g. DOC translated, DOCf translated, k translated, $L_0$ translated) can be translated into a SD model component with the associated program code as shown in Figure 6.

A




B

```
Accumulated_CH4(t) = Accumulated_CH4(t - dt) + (CH4) * dt
INIT Accumulated_CH4 = CH4
INFLOWS:
  CH4 = IF(Closure_year<Time1) THEN
  (((A*k_translated*MSW_mass*Lotrans)*(1-EXP(-k_translated*Time1))-OX)*(1-RX) ELSE
  (A*k_translated*MSW_mass*Lotrans)*(EXP(-k_translated*Time1)*-(EXP(k_translated*Ti
  me2))-OX)*(1-RX))

Codftrans =
(OM_mass*DOC_OM*DOCf_OM)+(paper_paperboard_masss*DOC_papeer*DOCf_paper)+(Text
iles_and_others_mass*DOC_textiles*DOCf_textiles)+(Wood_mass*DOC_wood*DOCf_wood)/(
OM_mass*DOC_OM)+(paper_paperboard_masss*DOC_papeer)+(Textiles_and_others_mass*
DOC_textiles)+(Wood_mass*DOC_wood)
```

***Figure 6.*** *(A) A diagram showing $CH_4$ flow rate determination and DOCf with STELLA; (B) associated program code.*

It can be assumed that SD is a reasonable approach for modeling leachate/biogas generation processes that are non-linear and occur in a feedback form. The data used for model calibration are present in Table 3 and were obtained from in situ experiments, documental data and traditional methodologies adapted for tropical and dumpsites management conditions in Brazil.

***Table 3.*** *Input parameter values used to SD model calibration.*

| Parameter | Value | Source |
|---|---|---|
| Mean Temperature [°C] | Time series measurements (21.875) | [67] |
| Mean Precipitation (1987 - 2020) [mm] | Time series measurements (115.6) | Meteorological station (Code: 2244041) |
| Mean Potential Evapotranspiration [mm] | 87.23 | Estimated |
| Mean Real Evapotranspiration [mm] | 79.84 | Estimated |

| Parameter | Value | Source |
|---|---|---|
| Field capacity [$m^3$ x $m^{-3}$] | 0.1616 | Estimated |
| Wilting Point (WP) [$m^3$ x $m^{-3}$] | 0.0951 | Estimated |
| $k_{sat}$ [cm x $s^{-1}$] | 2.6951 x $10^{-5}$ | Estimated |
| Cover soil volume [$m^3$] | 19551 | Documental data – Volta Redonda City Hall. |
| Cover layer thickness [m] | 0,5317 | Estimated |
| Total avaible soil water [mm $H_2O$ x $m^{-1}$] | 176.89 | Estimated |
| Soil water storage [mm] | 94.05 | Estimated |
| Total soil water storage for ETR calculation [mm x $year^{-1}$] | 719,9 | Estimated |
| Mean slope [%] | 2 | Measured from Slope Map |
| Effective soil area [$m^2$] | 36770,96 | Estimated from DTM |
| Runoff [mm] | 18.98 | Estimated |
| $\theta_{soil}$ [$m^3$ x $m^{-3}$] (mean volumetric soil water content) | 0.1457 | Estimated |
| $\theta_{residual}$ (WP≥0.04) [$m^3$ x $m^{-3}$] (residual soil-moisture content) | 0.03778 | Estimated |
| $\theta_{saturated}$ [$m^3$ x $m^{-3}$] (saturated soil moisture content) | 0.2865 | Estimated – (16) |
| α (van Genuchten parameter - pressure) [$cm^{-1}$] | 0.0316803 | Estimated – (4) |
| $\varphi_c$ [cm] bubbling pressure | 44.39 | Estimated |
| λ (pore size distribution index) | 2.05774 | Estimated |
| n (van Genuchten parameter - pore size distribution index) | 1.3695 | Estimated from Soil-Water Characteristic Curve |
| Food waste [%] | 53,03 | |
| Paper/cardboard [%] | 16,57 | |
| Textiles, garden waste, park waste or other non-food organic putrescible [%] | 5,62 | Documental data – Volta Redonda City Hall. |
| Wood or straw [%] | 0,65 | |
| MSW volume landfilled [$m^3$] | 516204,79 | Estimated from DTM. |
| MSW unit weight [ton x $m^3$] (compacted) | 0,7 | [68] |
| MSW natural content [%] | 0,6 | [69] |
| MSW weight landfilled [ton] | 361343,353 | Estimated |
| Methane potential predicted by stoichiometric equations - Cm [$m^3$ $CH_4$ x $ton^{-1}$ dry mass] | 499,31 | Estimated |
| Water consumption factor [$m^3$ $H_2O$ x $ton^{-1}$ dry mass] | 0,25694 | Estimated |
| Fraction DOC dissimilated by MSW type [% by mass] | Food waste - 0,64<br>Paper/cardboard – 0,37<br>Textiles, garden waste, park waste or other non-food organic putrescibles – 0,23<br>Wood – 0,21 | [70] |
| DOC by MSW type [% by mass] | Food waste – 0,15<br>Paper/cardboard – 0,4<br>Textiles, garden waste, park waste or other non-food organic putrescibles – 0,17<br>Wood – 0,3 | [71] |
| Methane Correction Factor – MCF [%] | 65 | [59] |
| Fraction of $CH_4$ in LFG [%] | 50 | Default [71] |
| DOC translated [% by mass] | 0,207366 | Estimated |
| DOCf translated [% by mass] | 0,496026 | Estimated |
| $L_0$ - Methane generation potential [$m^3$ $CH_4$ x $ton^{-1}$ MSW] | 62,1824 | Estimated |
| Waste decay rate [$year^{-1}$] | 0,2879 | Estimated |
| Methane density [ton x $m^{-3}$] | 0,0007168 | Specific dataset |
| Normalization factor [adimensional] | 0,869 | Estimated |
| MSW field capacity [%] | 32.73 | Estimated – (5) |
| Sand [%] | 69.8 | |
| Silt [%] | 14.8 | |
| Clay [%] | 15.4 | |
| Organic carbon [%] | 0.23 | [72] |
| Bulk density [Mg x $m^{-3}$] | 1,651 | |
| Particle density [Mg x $m^{-3}$] | 2.66 | |
| Initial soil water content [$m^3$ x $m^{-3}$] | 20.9 | |

The in situ data determination used in SD model proposed was conducted at the Volta Redonda uncontrolled landfill (22º 23' to 22º 40' S, 44º a 44º 12' W) Rio de Janeiro state, Brazil. This region presents a mesothermal tropical climate (Cwa), with maximum temperatures means of about 26,8°C and minimum temperatures means of about 16,8°C, and mean annual rainfall for 1987 – 2020 period of 1386.7 mm. The main cover soil characteristics are the sand content, silt content, clay content, bulk density, particle density, organic carbon content and initial soil water content presented in Table 3, with a mean slope of 2% and the Soil-Water Characteristic Curve shown in Figure 7.

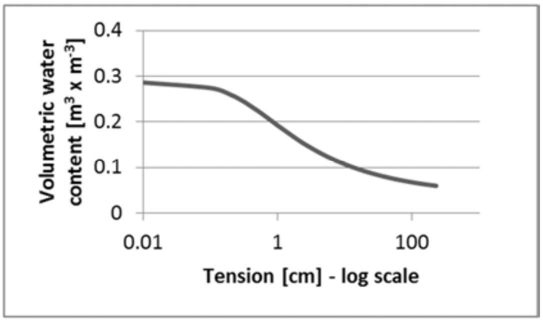



***Figure 7.*** *Soil water retention curve for sandy loam soil used to determination the soil water storage and unsaturated hydraulic conductivity.*

The model calibration process aims to obtain the best fit between the leachate observed data and simulated results. No real biogas production data are available therefore leachate accumulated is considered as targets for the calibration and validation. Nevertheless, the theoretical biogas production was compared with the LandGEM model (based on first-order decay equations) results adapted for local conditions by adjusting the input parameter values. LandGem is the most conventional, easily accessible, and reliable model due to its simplicity [73, 74].

The total weight landfilled and MSW gravimetric characteristics are necessary to perform the translating methane generation parameters (DOC, DOCf, $L_0$, and k) among first-order decay SD model operated independently - Biodegradation Module. The total precipitation, mean slope, real superficial area, cover layer thickness, mean air temperature, and soil characteristics are necessary to perform the soil water balance to obtain the deep percolation. The leachate and methane generated are simulated from these results. Primary climate data are necessary, but due to the complex acquisition the mean values observed in literature according to local conditions can be used. Figure 8 shows the comparisons between predicted accumulated leachate from the Swiss method and SD model during the model validation process on a monthly basis. The Swiss method (empirical formulations) was used in this research due to its simplicity (only need precipitation, real superficial area, and MSW compaction coefficient: k = 0,25) for comparative purposes. Table 4 shows the field data, preliminary calibration results for the 2007 – 2011 periods, and Root-Mean-Square Error (RMSE) for leachate production.

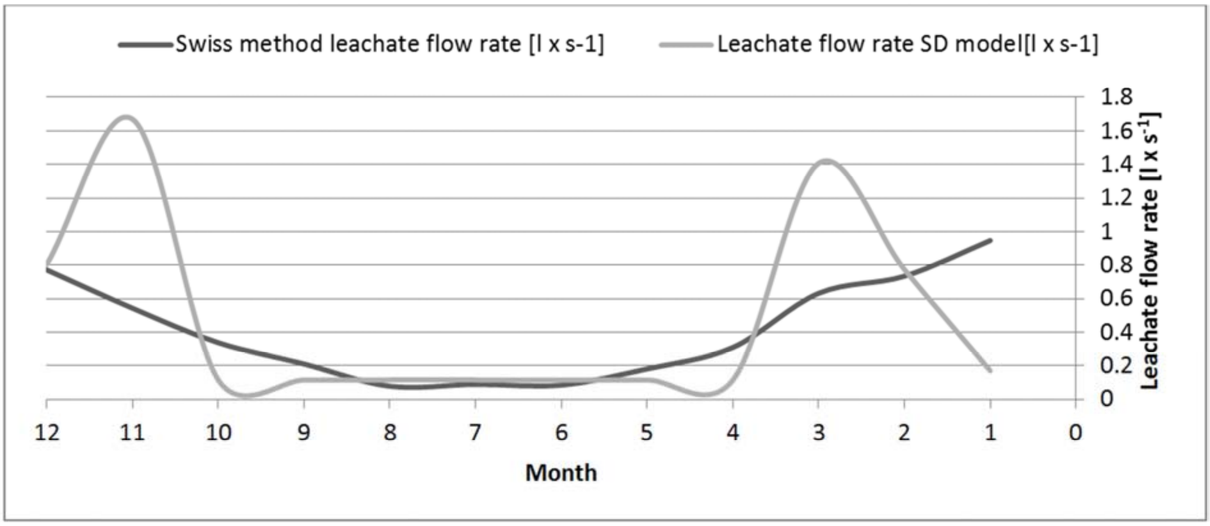



***Figure 8.*** *Comparison of the estimated flow between the studied methods.*

Despite the close annual mean leachate flow rates between Swiss method (0.4098 l/s) and SD model (0.4693 l/s), the difference between the curves indicates that in the Swiss method the precipitation instantly is transformed into percolation, and in the SD model the precipitation occurs and after soil wetting the deep percolation starts, reflecting the reality of the physical phenomenon (the highest rainfall are concentrated in January-March and November-December).

It is further verified that Real Evapotranspiration accounted for 69.1% of the precipitation and Runoff was the smallest component of the water balance accounted for 16,4% of the precipitation.

***Table 4.*** *Measured leachate flow rate, RMSE, and Standard Deviation for 2007 - 2011 period.*

| Years | Field data – annual mean leachate flow rate (l /s) | Residuals | Square Residuals | RMSE (total) | RMSE (without 2009 data) | Standard deviation (total) | Standard deviation (without 2009 data) |
|---|---|---|---|---|---|---|---|
| 2007 | 5,49 | 1,026730161 | 0,02150465 | | | | |
| 2008 | 5,51 | 1,022072615 | 0,01479742 | | | | |
| 2009 | 6,04 | 0,932318192 | 0,16720814 | 0.2036 | 0.10013 | 0.2230 | 0.0994 |
| 2010 | 5,69 | 0,989166863 | 0,00380550 | | | | |
| 2011 | 5,63 | 0,999651007 | 0,00000387 | | | | |

In 2010, leachate collection systems were installed and the flow was accumulated in treatment pond. Before the installation the leachate was directed to a collection tank where it were periodically pumped for ex-situ treatment with average daily flow rate of 39,50 m³/day, 39,68 m³/ day, 43,5 m³/day and 41,00 m³/day for the years 2007, 2008, 2009 e 2010 respectively. The leachate flow rate in 2011 was 40,57 $m^3$/day and after this year the measurements were no longer performed (Public Civil Action: ACP Nº. 0002992-48.2003.4.02.5104).

It can be assumed for Table 4 that the SD model fitted with higher accuracy with the real data, indicating differences less than 8% (2.60% - 2007; 2.15% - 2008; 7.25% - 2009; 1.09% - 2010; and 0.034% - 2011) with the exception of the 2009 year, which showed a difference of 7.25% due to the excess of precipitation (2043 mm) significantly larger (47.33%) than the mean precipitation of 1386.7 mm for 1987 – 2020 calculation period.

The RMSE statistics show a comparison of the actual difference between the estimated and the measured value for the 2007 – 2011 period of RMSE = 0.2036 and SD = 0.2230.

The RMSE statistics without 2009 data is more representative of the local system: RMSE = 0.10013 and SD = 0.0994. These values represent similar correlations between the SD model predictions and the experimental measurements. The smaller the RMSE value (RMSE = 0,10013) the better the model's performance.

Figure 9 shown methane generated rate using the SD model and the LAndGEM model adapted to local conditions.

It can be seen that the shape function showed high similarity between the two models which indicates the convergence in the parameters modeling used in the SD model, nonetheless, the numerical difference of the methane accumulated for a 100-year time horizon (1987 - 2087) is 4.566.368,71 $m^3$ or 3.273,17 ton $CO_2$eq. The difference of 85,62% between the two models can be explained by the $L_0$ and k calculations. The SD model considers that each of the components has unique methane generation parameters and is calculated by translating the multiphase parameters through weighted-average waste stream for input into a single-phase, obtaining the bulk waste characteristics (DOC, DOCf, $L_0$, and k). LandGEM model assumes homogeneity composition of waste and does not consider seasonal temperature and precipitation that present strong correlations with landfill gas components, total water content (accumulated leachate) and cover soil.

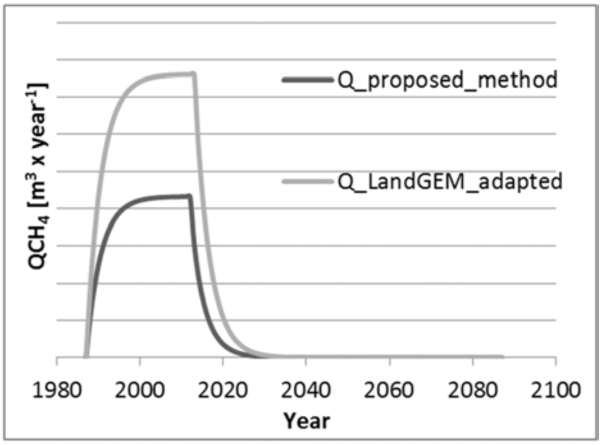



*__Figure 9.__ Emissions estimates relation between SD model and adapted LandGEM model.*

The SD model considers MSW split into components by translating their parameters to produce the equivalent amount of methane determined by bulk $L_0$ and total mass [75]. The LandGem model overestimate methane generation [53, 76]. Even when the optimized parameters (k, $L_0$ or DOC) are used in LandGem model the results still remains high with mean percentage error between 3% to 12% and residual sums of squares (RSS) between 60% - 98% over the default approach (results from seven landfill in temperate climate conditions with accurate forecasting). The LandGEm model was especially developed for temperate climate [77-79].

Table 5 provides the results of the translating parameters as gas generation rate constant (k), methane generation potential ($L_0$), degradable organic carbon (DOC), and fraction of DOC dissimilated (DOCf) and set of parameters at wet landfills.

***Table 5.*** *Translating parameters - $L_0$, k, DOC and DOCf.*

| $L_0$ [$m^3$ $CH_4$/waste ton] | k [$year^{-1}$] | DOC [% by mass] | DOCf [% by mass] | Observations | Source |
|---|---|---|---|---|---|
| 62,182 | 0,2879 | 0,207 | 0,496 | Calculation period 1987 - 2087 | ESTIMATED |
| 100 | 0,3 | - | - | Conservative parameters | [80] |
| 66,62 | 0,21 | - | - | Fitted results according to IPCC | [52] |
| 58,37 (Nova Iguaçu Landfill) | 0,17 | - | - | Fitted results according to IPCC | [81] |
| 73,01 (Bandeirantes Landfill) | 0,17 | | | | |
| 68,71 (Paulínia Landfill) | 0,17 | | | | |
| 75,43 (Caieiras Landfill) | 0,09 | | | | |
| 96 | 0,7 | - | - | Wet landfills | [82] |
| - | - | 0,144 | | Fitted results according to IPCC | [83] |
| | | 0,189 | | Fitted results according to LandGem | |
| 60,30 | 0,33 | - | - | Controlled landfill | [84] |
| 64,12 | | | | Controlled Landfill | |
| 23,08 | | | | Dumpsite | |
| 31,22 | | | | Dumpsite | |

The chemical constituent values were close to the results presented by Machado [85]. It was found that k was 0,2879 $yr^{-1}$ which is equivalent to 2,4 years (half-life= ln2/k) and was higher than the 0.17 $yr^{-1}$ suggested by IPCC for tropical wet climate. The high temperature, high moisture content, and high food waste content (53,03%) of the waste at wet landfills are favorable for accelerating the biological decomposition which implies a higher rate of gas generation rate constant, methane generation potential, degradable organic carbon, and a fraction of DOC dissimilated. The k, $L_0$, DOC, and DOCf values obtained are compatible with suggested values in different research over time.

The limitation of the SD modeling approach is the static MSW quantity conditions. The model was developed only for controlled landfills that are in decommissioned phase and the disposal activities are no longer available. Nevertheless, the structure formation processes perform calculations of biological processes over time and estimate the changes in water storage. It was considered that k and $L_0$ values did not vary during the simulation. Furthermore, some mean values as MSW field capacity may affect the leachate generation rates and need to be determined by laboratory analysis.

The real evapotranspiration, calculated by Thornthwaite and Mather method produced highly accurate despite the meteorological data scarcity. Penman-Monteith FAO model and water retention function could be introduced to the SD model when specific data was available.

The results of this simulation make it possible for the administration to design control structures with high precision and to knowledge different interrelationships concerning leachate/biogas generation with a few data available.

# 4. Conclusions

The proposed model provides an SD approach based on limited data that can be used to estimate the LFG parameters for wet landfills applied with MDT results.

The data obtained from Unmanned Aerial Vehicle (UAV) survey developed with a total station (TS) were used to generate the DTM in dangerous and inaccessible areas. The spatial resolution of 4,3 cm represents the terrain adequately with prediction errors of $RMSE_X$ = 0,07287 m, $RMSE_Y$ = 0,041791 m, and $RMSE_Z$ = 0,232317 m indicating high precision for this survey. The volume of MSW landfilled estimated was central for the SD model simulation.

The available parameters suggested in the literature (k, $L_0$, DOC, and DOCf) based on theoretical modeling, in situ measures, laboratory analysis as BFw, and others methodology give good results if adapted to local conditions.

The waste gravimetric composition is fundamental to obtaining good estimates of biogas production. Translating LFG parameters does not overestimate the biogas flow rates when compared with LandGem model results. The LFG parameters rates were similar to the reported in the literature for similar sites – wet landfills in a tropical climate.

The modeling results reflected the observed leachate flow even with a limited set of climatological data: RMSE = 0.2036 and SD = 0.2230 (2007 – 2011 period) and RMSE = 0.10013 and SD = 0.0994 (without 2009 data). The total accumulated precipitation for the year 2009 of 2043 mm was significantly higher than the average of 1406 mm (1987 - 2015), which is directly reflected in the leachate generation in the area, increasing the RMSE.

In summary, the SD model allowed to estimate the soil water fluxes, leachate generation, and biogas production for an area without climatological and operating data.

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