MATHEMATICAL MODELLING OF BIOGAS FROM MUNICIPAL SOLID WASTE LANDFILL

G. MANNINA*; D. DI TRAPANI*; G. VIVIANI*

* Dipartimento di Ingegneria Civile, Ambientale, Aerospaziale, dei Materiali, Università di Palermo, Palermo, Italy

Keywords: mathematical modelling; landfill gas; moisture distribution; vertical leachate flow

Abstract. *Sanitary landfills for municipal solid wastes can be considered as large biological reactors where the organic fraction of municipal solid waste undergoes anaerobic digestion producing gas and liquid emissions. Leachate production from municipal sanitary landfills is currently recognized as a major environmental burden associated with municipal solid waste management and it may be responsible for local pollution of groundwater and soil. Moreover, the fate of the organic compounds within the landfill body is of primary importance since it directly influences the production of landfill gas. The aim of the paper is to propose an integrated mathematical model able to simulate, on one hand, the vertical leachate fluxes throughout a municipal solid waste landfill (considering the fate of both inorganic and organic contaminants within the landfill leachate pathway), while, on the other hand, the production of landfill gas by means of two different approaches. In detail, the mathematical model was based on mass balance equations and was composed by two sub-models: one for the simulation of moisture distribution, whilst the other one for the simulation of the organic/inorganic contaminant concentrations. The simulation of landfill gas production was based on two different approaches. The integrated model has been applied to a real landfill considered as a case study, the landfill of Pescantina (Italy), with the landfill body divided into N horizontal layers. The results confirmed that the proposed integrated model can be a useful tool for the landfill operator in order to analyze the physical, chemical and biological phenomena occurring within the landfill body.*

1. Introduction

Sanitary landfilling has been by far the most adopted method in many Countries for managing the final disposal of municipal solid waste (MSW), often without any pre-treatment of the disposed waste (Fellner and Brunner, 2010). Therefore, sanitary landfills for MSWs can be considered as large biological reactors where the organic fraction of MSWs undergoes anaerobic digestion producing gas and liquid emissions (Imhoff et al., 2007). Referring in particular to liquid emissions, rainfall infiltration, coupled with the original moisture content of the waste, contributes to transporting pollutants and inhibitory compounds within the landfill body, leaching out organic and inorganic compounds. Leachate production from municipal sanitary landfills is currently recognized as a major environmental burden associated with MSW management and it may be responsible for local pollution of groundwater and soil (Beaven et al., 2001). In the last decades, many efforts have been devoted by

the scientific community with the aim to increase the comprehension of the mechanisms of leachate generation as well as to develop mathematical models that should be able to provide reliable predictions of leachate production as well as its qualitative features, in terms of both inorganic and organic compounds (Straub and Lynch, 1982). Since water plays a key role in landfills, knowledge about its distribution and transport is fundamental for understanding the behavior of the landfill as a reactor. Several studies have been carried out with the aim to understand leachate migration characteristics and its spatial and temporal variations during either landfill operation or after closure (El Fadel et al., 1997; Fellner and Brunner, 2010). Moreover, the fate of the organic compounds within the landfill body is of primary importance since it directly influences the production of landfill gas (LFG). Indeed, the biodegradable portions of organic compounds that are hydrolyzed and dissolved in the liquid phase will be eventually subjected to anaerobic degradation, thus producing LFG, mostly composed of methane (CH_4), carbon dioxide (CO_2), and trace components. CH_4 has been recognized as one of the most significant contributor to global warming (IPCC, 2007), since it more effectively adsorbs infrared radiation than CO_2, having a global warming potential (GWP) index of 25 over a 100-year time horizon (Scheutz et al., 2009). Moreover, MSW landfills have been identified as one of the most important anthropogenic sources of CH_4 emission. Therefore, it is crucial to have reliable estimates of LFG production within a landfill. The simulation of LFG production has been carried out by means of two different approaches: i) the model proposed by Andreottola and Cossu (1988); ii) the approach proposed by Caserini (1994).

Bearing in mind these considerations, the aim of the paper is to propose an integrated mathematical model able to simulate, on one hand, the vertical leachate fluxes throughout a MSW landfill (considering the fate of both inorganic and organic contaminants within the landfill leachate pathway), while, on the other hand, the production of LFG by means of two different approaches. Referring ion particular to inorganic contaminant, the model enabled the simulation of chlorides and manganese concentrations (Di Trapani et al., 2015b). The model was based on mass balance equations and the simulation of continuous moisture distribution was carried out according to the theory of the vertically distributed unsaturated flow according to Straub and Lynch (1982). The integrated model has been applied to a real landfill considered as a case study, the landfill of Pescantina (Italy), with the landfill body divided into N horizontal layers characterized by the same thickness. The model results were compared with real data provided by the landfill operator. The main goal of the present work was to gain insight about the fate of leachate pathways as well as the fate of organic contaminants within the landfill body, that will contribute to LFG production.

2. Methods

2.1. The landfill site

The case study landfill is located in the county of Pescantina (VR), in Northern Italy. The nearest inhabited locality is about 1.8 km far form the landfill in nord direction. The landfill was realized in the middle of the 80s and covers an area of about 12 ha. The landfill is composed by 8 cells for waste disposal. Four cells located on the western portion of the area were operative in the period 1987-1999, whilst the further fours in the period from 1999 to 2006. The landfill is limited at the north by the mountains and at the south by the railway. The landfill was used for MSW disposal and, at present, it is in the post-operational period. The leachate volumes drained at

the bottom of the landfill were provided by Daneco Gestione Impianti S.p.A. Company, landfill operator. Quality data in terms of chlorides and manganese concentrations have been provided by ARPAV, the local Government Agency for environmental quality monitoring. A rain gauge is installed inside the landfill area and the data recorded in the last 10 years have been used to generate the net rainfall flow to be used as input of the model. Figure 1 reports the aerial view of the Pescantina landfill.

Figure 1. *The landfill of Pescantina (VR): aerial view*

2.2. Model description

2.2.1. Simulation of the vertical leachate flux and contaminants distribution

As aforementioned, the paper presents a simple 1-D model for the simulation of the vertical leachate fluxes throughout a landfill for MSW and its application to a real Italian landfill as case study. In particular, the model is composed by two sub-models: the first one (quantity sub-model) aimed at simulating the moisture distribution, while the second one (quality sub-model) aimed at assessing the concentrations of inorganic/organic contaminants within the landfill body. The model was based on mass balance equations, which allow the evaluation of the moisture accumulation inside the landfill body as well as the concentration of inorganic/organic (conservative/non-conservative) contaminants.

Concerning the assessment of the liquid movement throughout the landfill, the model enables to calculate the moisture content, on the basis of a simple 1-D model proposed recently by Di Bella et al. (2012). Briefly, the simulation of continuous moisture distribution was carried out basing on the theory of the vertically distributed unsaturated flow according to Straub and Lynch (1982). In particular, a moisture mass balance written over a differential volume subjected to vertical flow gives:

$$\frac{\partial \theta}{\partial t} + \frac{\partial q_v}{\partial z} = -r \qquad (1)$$

where θ is the volumetric moisture content (m m^{-1}); qv is the vertical flux on moisture (m s^{-1}); r is the moisture sink (m m^{-1} s$_{-1}$); t is the time (s) and z is the length (m), assumed positive downwards.

The vertical flow q_v was calculated by means of the application of Darcy's law for an unsaturated porous medium according to Childs (1967):

$$q_v = K(\theta) - D(\theta) \cdot \frac{\partial \theta}{\partial z} \qquad (2)$$

where K is the unsaturated moisture conductivity (m s^{-1}); D is the moisture diffusivity (m^2 s^{-1}) and the other symbols were previously defined. Both parameters are not constant, depending by moisture variation. Substitution of Eq. (2) into Eq. (1) yields the equation of unsaturated moisture flow (Richards equation):

$$\frac{\partial \theta}{\partial t} = -\frac{\partial K(\theta)}{\partial z} + \frac{\partial}{\partial z}\left(D(\theta)\frac{\partial \theta}{\partial z}\right) - r \qquad (3)$$

For further details about model structure, the reader is referred to literature (Di Bella et al. 2012; Di Trapani et al., 2015a,b).

Referring to quality sub-model, the simulation of contaminant concentrations has been carried out by integrating in the existing model a mass balance equation written for the generic contaminant, which yields:

$$\frac{\partial}{\partial t}(C\theta) + \frac{\partial}{\partial z}(Cq) + \frac{\partial}{\partial z}J = R_t\theta \qquad (4)$$

where C is the contaminant concentration (mg L^{-1}); R_t is the contaminant production rate (mg L^{-1} s^{-1}); J is the combined diffusive/dispersive flux (mg m^{-2} s^{-1}) while θ has been previously defined. On the other hand, differentiation of Eq (4) and combination with Eq (1) gives the equation of contaminant transport:

$$\frac{\partial C}{\partial t} + \frac{q}{\theta}\frac{\partial C}{\partial z} + \frac{1}{\theta}\frac{\partial J}{\partial z} = R_t + \frac{C}{\theta}r \qquad (5)$$

It was assumed that the combined diffusive/dispersive flux J was characterized by two components: the molecular diffusion and the hydraulic dispersion. The combination of these two aspects can be expressed as follows:

$$J = -E\frac{\partial C}{\partial z} \qquad (6)$$

where E is the diffusion/dispersion coefficient of the specific contaminant.

Concerning the organic contaminants (non conservative), once released form the waste to the liquid phase, they will be further metabolized by the bacterial consortium, thus contributing to LFG production. The rate of substrate utilization Ru has been simulated according to Collivignarelli and Conte (1985):

$$R_u \frac{dc}{dt} = \frac{1}{Y}\frac{\mu_{H,max}XC}{K_m + C} \qquad (7)$$

where R_u is the substrate utilization rate (mg L^{-1} d^{-1}), X is the biomass concentration (mg L^{-1}), Y is the biomass yield coefficient (mgCOD mg^{-1}COD), $\mu_{H,max}$ is the maximum growth rate (d^{-1}), Km is the half saturation coefficient (mg L^{-1}) and C has been previously defined.

The organic contaminant contained in the waste decreases over time since it is released into the liquid phase. This aspect can be expressed as follows:

$$\frac{dS}{dt} = -V \cdot \theta_{sat} \cdot R_g \tag{8}$$

where S is the contaminant amount at time t (mg), θ is the saturated volumetric moisture content (m m^{-1}), Rg is the contaminant release rate (mg L^{-1} d^{-1})

Moreover, the solution of the equation of contaminant transport requires the evaluation of dispersion/diffusion term E as well as the contaminant production rate R_t.

Referring to dispersion/diffusion term E, Breseler (1973) proposed a formulation of the hydraulic dispersion coefficient proportional to water infiltration rate. Neglecting molecular diffusion, the coefficient E can be expressed as:

$$E(V) = \lambda |V| \tag{9}$$

where $V = q/\theta$ is the infiltration rate and λ is a constant, having the dimensions of length and is considered a property of the porous medium.

On the other hand, the contaminant production rate R_t can be estimated according to what reported by Straub and Lynch (1982), yielding the following expression:

$$R_{ti}^k = \frac{S_i^k}{S_0} b_l \left(C_{max} - C_i^k \right) \tag{10}$$

where S_i is the leachable contaminant remaining (mg), $S_{i,0}$ is the original leachable contaminant (ultimate source of contaminant in waste) (mg), b_l is a rate constant (s^{-1}) and C_{max} is the maximum concentration of contaminant in the liquid phase, at saturation condition (mg L^{-1}). The latter expression is based on the assumption that the generation rate is proportional to the difference between concentration and saturation concentration (Straub and Lynch, 1982).

2.2.2. Simulation of landfill gas production

Once achieved the organic contaminant simulation by means of the leachate quality sub-model, it was possible to simulate the LFG production by means of two different approaches:

i)   the model proposed by Andreottola and Cossu (1988), which is based on first-order reaction kinetics and that takes into account the influence on the gasification process of structural and operational features of the landfill such as humidity, bulk density and size of waste;

ii) the approach proposed by Caserini (1994) that assesses the depletion dynamics of the biodegradable organic matter directly from the solid phase by employing the empirical kinetics typical of methanogenesis.

The two approaches enables the LFG generation starting from the knowledge of the biodegradation phenomena of the organic fraction under anaerobic conditions.

Concerning the approach proposed by Andreottola and Cossu (1988), the model takes into account the heterogeneity of the solid liquid phase and the substrate hydrolysis (eg its transportation from the solid to the liquid phase) as well as the waste heterogeneity, differentiating among the rapidly and slowly biodegradable organic matter.

Conversely, the model proposed by Caserini (1994) the LFG generation is simulated on the basis of two distinct kinetic rates: "production" and "depletion".

Figure 2 reports the conceptual scheme of the model, which is employed to simulate the landfill, the leachate pathway and the LFG production.
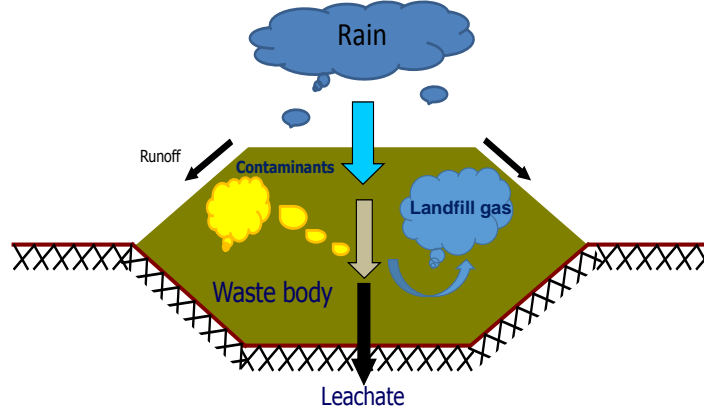

Figure 2. *Conceptual scheme of the model*

2.3. Numerical formulation scheme

Referring to the numerical formulation, the solution of the mathematical model equations, highly non-linear, was assessed by an explicit finite difference. Briefly, the numerical scheme was of order 1 in time and order 2 in space and the landfill body was divided in N layers of same height equal to 0.1 m (Di Trapani et al., 2015).

According to such assumptions, Eq (3) and Eq (5) can be rewritten as follows:

$$\theta_i^{k+1} = \theta_i^k - \frac{\Delta t}{\Delta z}(K_i - K_{i-1})^k + \frac{\Delta t}{\Delta z^2}[D_{i+1/2}(\theta_{i+1} - \theta_i) - D_{i-1/2}(\theta_i - \theta_{i-1})]^k - \Delta t(r_i^k) \tag{11}$$

$$C_i^{k+1} = C_i^k - \frac{\Delta t}{\Delta z}\left[\frac{q_{i-1}}{\theta_i}(C_i - C_{i+1})\right]^k + \frac{\Delta t}{\Delta z^2}\left[E_{i+\frac{1}{2}}(C_{i+1} - C_i) - E_{i-\frac{1}{2}}(C_i - C_{i-1})\right]^k + \Delta t(R_{ti} - R_{ui})^k \tag{12}$$

$$R_{gi}^k = \left(\frac{s_i^k}{s_{i0}}\right)^m b_1(C_{max} - C_i^k) \tag{13}$$

where Δt is the time step (s), Δz is the height of the layer employed in the finite difference scheme (m), while sub and superscripts i and k represent respectively the number of the layer and the time. The other symbols have been previously defined.

The following boundary conditions have been imposed, with the aim to enable the simultaneous solution of the equations represented by (9) and (10):

- at time t = 0, same moisture content in the whole landfill height;
- at the upper layer the input was the rate of addition of rainfall water to the landfill;

- at the landfill bottom, the moisture flux is by gravity drainage only.

Therefore, the equations for the upper layers are:

$$\theta_1^{k+1} = \theta_1^k - \frac{\Delta t}{\Delta z}(K_1)^k + \frac{\Delta t}{\Delta z^2}[D_{1+1/2}(\theta_2 - \theta_1)]^k + \Delta t \left(\frac{q_0}{\Delta z} - r_1\right)^k \qquad (14)$$

$$C_1^{k+1} = C_1^k - \frac{\Delta t}{\Delta z}\left(\frac{q_0}{\theta_1}\right)(C_1 - C_0)^k + \frac{\Delta t}{\Delta z^2}\left[E_{i+\frac{1}{2}}(C_2 - C_1)\right]^k + \Delta t\left[R_t + \frac{s_1 C_1}{\theta_1}\right]^k \qquad (15)$$

where q_0 is the net flow rate infiltrating per unit area of the upper layer (m s^{-1}).

At node n (bottom layer), assuming no moisture diffusion out of the system and moisture flux by gravity drainage only, the moisture diffusivity D and the diffusion/dispersion coefficient E are null; therefore, the equations are:

$$\theta_n^{k+1} = \theta_n^k - \frac{\Delta t}{\Delta z}(K_n - K_{n-1})^k + \frac{\Delta t}{\Delta z^2}[D_{n-1/2}(\theta_n - \theta_{n-1})]^k - \Delta t(r_n^k) \qquad (16)$$

$$C_n^{k+1} = C_n^k - \frac{\Delta t}{\Delta z}\left[\frac{q_{n-1}}{\theta_n}(C_n - C_{n-1})\right]^k + \frac{\Delta t}{\Delta z^2}\left[E_{n-\frac{1}{2}}(C_n - C_{n-1})\right]^k + \Delta t\left[R_n + \frac{s_n C_n}{\theta_n}\right]^k \qquad (17)$$

As previously discussed, the simulation of the LFG production has been carried out by means of two different approaches. According to the model proposed by Andreottola and Cossu (1988), the amount of the biodegradable organic carbon contained in each waste fraction can be expressed according to the following Eq (18):

$$Cbio_i^k = C_i^k V C_C f_{bc}\left[\left(1 - \theta_i^k\right)p\right] \qquad (18)$$

where $Cbio_i^k$ is biodegradable organic carbon contained into the waste (kg kg^{-1}), C_i^k is the organic contaminant concentration in the liquid phase (kg m^{-3}), V is the landfill volume (m^3), C_C is the organic carbon of the MSW component (kg kg^{-1}), f_{bc} is the biodegradable fraction of the organic carbon C_C (-), p is the wet weight of the component (kg kg^{-1}). Sub and superscripts i and k represent respectively the number of the layer and the time, while θ has been previously defined.

Actually, the carbon available for LFG generation is only a fraction of the biodegradable one, since a portion is used for biomass growth. This fraction depends on the temperature and can be expressed as follows:

$$Cbiogas_i^k = Cbio_i^k \cdot (0.014T + 0.28) \qquad (19)$$

where Cbiogasik is the organic carbon available for LFG production contained into the waste (kg kg-1), T is the temperature (°C) and Cbioik has been already defined. Sub and superscripts i and k represent respectively

the number of the layer and the time.

Finally, the specific LFG production can be expressed as follows:

$$g_i^k = 1.868 \cdot Cbiogas_i^k \cdot k_j \cdot e^{\left(-k_{ej} \cdot \Delta t\right)} \qquad (20)$$

where g_i^k is the specific LFG production m3 tonn-1), k_j is the maximum reaction rate (d-1), k_{ej} is the actual reaction rate (d-1) and Dt is the time step (d). Sub and superscripts i and k represent respectively the number of the layer and the time and $Cbiogas_i^k$ has been already defined.

On the other hand, the model proposed by Caserini (1994) is composed by two different phases: the production phase, characterized by an increasing LFG production, expressed by Eq(21):

$$G_i^k = G_i^{k-1} + K_1 \cdot G_i^{k-1} \cdot \Delta t \qquad (21)$$

And the depletion phase, simulated as follows:

$$G_i^k = G_i^{k-1} + K_2 \cdot G_i^{k-1} \cdot (G_{tot} - G_i^{k-1}) \qquad (22)$$

where G_i^k is the produced LFG (m^3), K_1 and K_2 are the kinetic constants and G_{tot} is the maximum LFG production rate. Sub and superscripts i and k represent respectively the number of the layer and the time.

2.4. Model calibration

Model calibration was carried out by means of the Generalized Likelihood Uncertainty Estimation (GLUE) methodology. GLUE was first proposed by Beven and Binley (1992) as a framework for the estimation of uncertainty from equally acceptable models or parameter sets. Briefly, parameter sets are classified by means of a likelihood measure and sets with poor likelihood weights, with respect to a user-defined acceptability threshold (Tr), are discarded as "non-behavioural". Conversely, all parameters sets coming from the behavioural simulation runs are retained and their likelihood weights are re-scaled so that their cumulative total sum is equal to 1. Therefore, the likelihood measure represents the ability of the model to fit real data. On the other hand, the acceptability threshold Tr represents a user-defined critical value indicating the minimum value of the likelihood measure that each modelling simulation should have to be representative of the model behaviour referring to the analysis target. Tr is usually set equal to zero. In the present study, the Nash and Sutcliffe efficiency index has been used as a likelihood measure (Nash and Sutcliffe, 1970):

$$E = L(\vartheta_i / Y) = \left(1 - \frac{\sigma_i^2}{\sigma_o^2}\right) \qquad with \qquad \sigma\_i\text{^2} < \sigma\_0\text{^2} \qquad (23)$$

where $L(\theta i/Y)$ is the likelihood measure for the i_{th} model simulation for parameter vector θ_i, conditioned on a set of observations Y, σ_i^2 is the associated error variance for the i_{th} model, and σ_{20} is the observed variance for the period under consideration. It is worth noting that, in agreement with other likelihood measures, the Nash–

Sutcliffe index is less than or equal to zero for all simulations that are considered to exhibit behavior dissimilar to that expected for the system under study, and increases monotonically as the similarity in behaviour increases, reaching a maximum value equal to 1 (Mannina and Viviani, 2010).

3. Results and discussion

3.1. Vertical leachate flux and contaminants distribution

Figure 3 shows the dynamic simulation results and measured values referring to the cumulative leachate volumes collected at the landfill bottom. As noticeable, the model is generally able to reproduce the measured values in a satisfactory way. Therefore, the calibrated simulation results show the capability of the developed model to approach the real landfill hydrology.
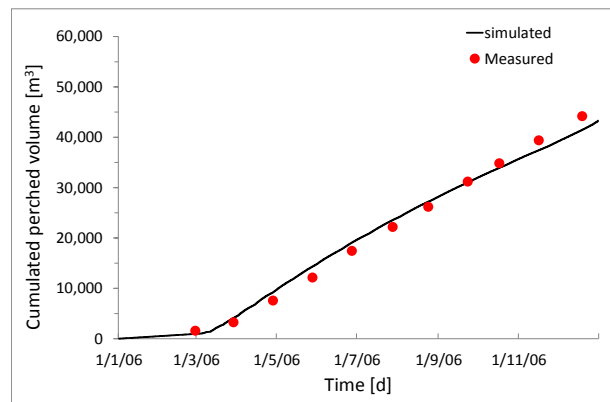

Figure 3. *Model results for cumulative leachate volumes*

Concerning the simulation results of inorganic contaminants as well as the calibration results, the reader is kindly addressed to literature (Di Trapani et al., 2015b).

Figure 4 reports the simulated chemical oxygen demand (COD) concentrations in the liquid phase, depending on the adopted release constant.
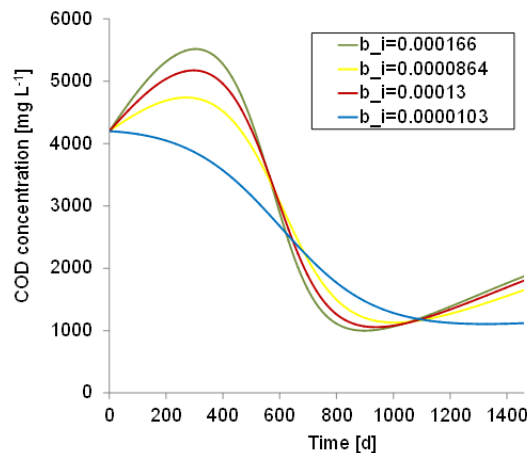

Figure 4. *COD concentrations in the liquid phase depending on the release constant*

From the observation of Figure 4, one can notice that the release constant b_i influences significantly the COD concentrations in the left portion of the graph, and in particular for a time period loess than 500 days. For a longer time period the simulation results highlight only a moderate influence of the b_i parameter, with similar COD concentrations in the liquid phase after 1400 days. This result is in good agreement with previous experiences reported in the technical literature (Collivignarelli and Conte, 1985).

3.2. Simulation results of LFG production

Once achieved the simulation results of the organic contaminant released from the MSW to the liquid phase, it was possible to simulate the LFG production from the deposited MSW. As aforementioned, the simulation of LFG production was carried out by means of two different approaches: the model proposed by Andreottola and Cossu (1988) and the model proposed by Caserini (1994).

Referring to the approach proposed by Andreottola and Cossu (1988), the model input is represented by the biodegradable organic carbon that will be used as substrate by the bacterial strains.

Given the unavailability of direct measurements, literature data have been used for the different waste fractions (Table 1).

The temperature value has been set equal to 40°C for the entire landfill depth, while the biodegradation rate values are reported in the following Table 2, together with the waste size.

Table 1. *Organic content and biodegradable fraction in the different waste fractions*

Waste fractions	C_i (%)	f_b (%)	Biodegradable compounds (%)	
Food and kitchen waste	0.48	0.8	Rapidly	33
Garden and park waste	0.48	0.7	Moderately	24
Paper	0.44	0.5	Slowly	32
Plastic	0.7	0.0		
Textiles and leather	0.55	0.2		
Wood	0.5	0.5		
Glass	0.0	0.0		
Metals	0.0	0.0		

Table 2. *Biodegrading rates and sizes of the different waste fractions*

Waste biodegradability	Maximum rate k_j (year^{-1})	β
Rapidly	0.693	0.5
Moderately	0.139	0.5
Slowly	0.046	0.5

Figure 5 reports the specific LFG production for the different organic fractions (Figure 5a), coupled with the LFG production during time (Figure 5b), in agreement with the limits reported by Straub and Lynch (1982).

Conversely, according to the approach proposed by Caserini (1994), it was supposed that the organic contaminant load is removed directly from the solid phase. Figure 6 reports the temporal pattern of organic matter degradation.
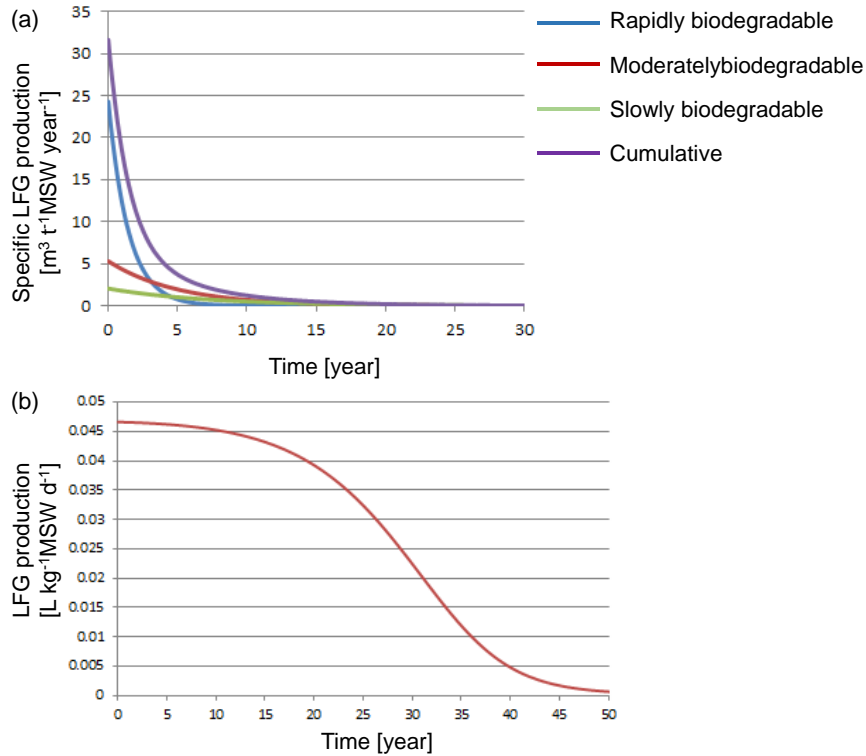
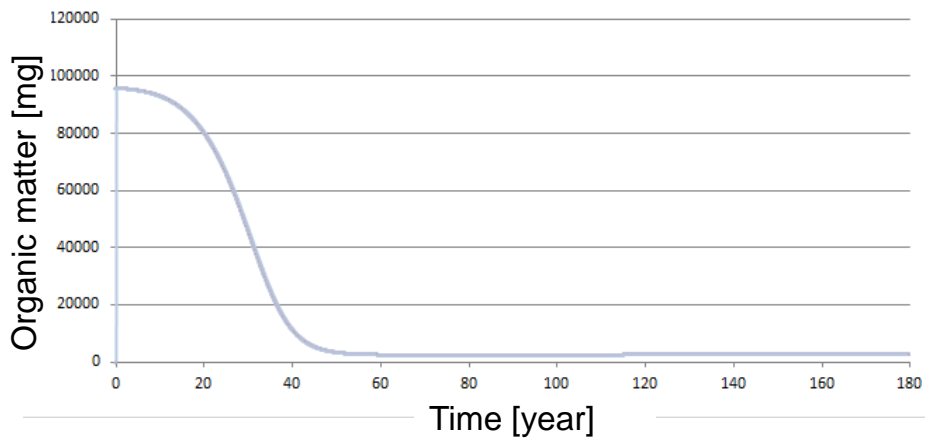**Figure 5.** *Specific LFG production (a) and temporal LFG production (b)*

Figure 6. *Temporal pattern of organic matter degradation*

According to what above mentioned, the approach proposed by Caserini (1994) is based on two distinct kinetic rates, "production" and "depletion"; in the present study the production constant rate k_1 was set equal to 0.004 d^{-1}, whilst the depletion constant rate was equal to 0.00003 d^{-1}. Moreover, the LFG produced is proportional to the mass of organic matter that is degraded through a coefficient α. The latter was set equal to 0.5, 0.6 and 0.7 for three different simulation scenarios, respectively. Figure 7 depicts the simulation results of the temporal LFG production, depending on the α coefficient value.
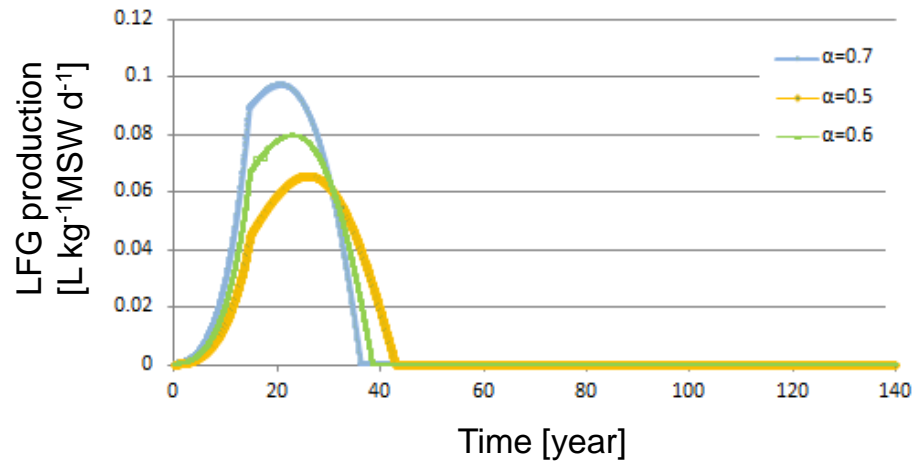
Figure 7. *Temporal pattern of LFG production according to Caserini (1994)*

On the basis of what suggested by the technical literature (Straub and Lynch, 1982), the simulation results characterized by higher likelihood is that one achieved for $\alpha = 0.5$. The observed results confirmed that the proposed integrated model can be a useful tool for the analysis of the physical, chemical and biological phenomena occurring inside the landfill body.

4. Conclusions

The paper presented the results of a simple 1-D model aimed at assessing the moisture distribution as well as fate of inorganic and organic contaminants within a landfill body. The model was composed by the integration of a quantity sub-model, aimed at evaluation the moisture distribution and thus the leachate volumes produced by the landfill body and a quality sub-model, aimed at assessing the fate of inorganic/organic contaminants into the landfill body. Moreover, the model enabled the simulation of LFG production by means of two different approaches. The model was applied to a real Italian landfill as case study. The obtained results highlighted the model ability to reproduce the real experimental data, referring in particular to the leachate volumes produced and suggesting that the proposed integrated model can be a useful tool for the analysis of the physical, chemical and biological phenomena occurring inside the landfill body.

References

[1] Andreottola G.,Cossu.,1988. Modello matematico di produzione del biogas in uno scarico controllato". Rifiuti Solidi 2, 473-483 (in italian).

[2] Beaven R., Knox K. and Croft B. 2001. Operation of leachate recirculation trial in a landfill test cell. In: Christensen, T.H., Cossu, R., Stegmann, R. (Eds.). Proceedings of the, Eighth International Waste Management and Landfill Symposium, Sardinia, pp. 595–604.

[3] Beven, K.J. Binley A.M. 1992. The future of distributed models – model calibration and uncertainty prediction, Hydrol. Proc., 6, 279–298.

[4] Bresler, E. 1973. Simultaneous Transport of solutes and Water under Transient Unsaturated Flow Conditions. Water Resour. Res. 9.

[5] Caserini S.1994. Modelli di previsione delle caratteristiche qualitative del percolato parte I: fondamenti teorici''. Rifiuti Solidi 5, 317-325.

[6] Collivignarelli, C., Conti, F. 1985. Modelli previsionali delle caratteristiche del percolato di discariche di rifiuti solidi – aspetti qualitativi. Rifiuti Solidi 3(1) (in Italian).

[7] Di Bella G., Di Trapani D., Mannina G. and Viviani G. 2012. Modelling of perched leachate zone formation in municipal solid waste landfills. Waste Manag. 32, 455-461.

[8] Di Trapani, D., Di Bella, G., Mannina, G., Nicosia, S., Viviani, G. 2015a. Influence of the Height of Municipal Solid Waste Landfill on the Formation of Perched Leachate Zones. J. Environm. Eng. 141. http://dx.doi.org/10.1061/(ASCE)EE.1943-7870.0000950.

[9] Di Trapani, D., Mannina, G., Viviani, G. and Babikova, K. 2015b. A quantity-quality mathematical model for municipal solid waste landfill: model calibration and sensitivity analysis. Proceedings Sardinia 2015, Fifteenth International Waste Management and Landfill Symposium, Cagliari, Italy; 5 – 9 October 2015.

[10] El-Fadel, M., Findikakis, A. N., Leckie, J. O. 1997. Modeling Leachate Generation and Transport in Solid Waste Landfills. Environm. Technol. 18, 669–686.

[11] Fellner, J., Brunner, P.H., 2010. Modeling leachate generation from MSW landfills by a 2-dimensional 2-domain approach. Waste Manage. 30, 2084-2095.

[12] Imhoff, P.T., Reinhart, D.R., Englud, M., Gue´rin, R., Gawande, N., Han B., Jonnalagadda, S., Townsend, T.G.. Yazdani, R., 2007. Review of state of the art methods for measuring water in landfills. Waste Manag. 27, 729–745.

[13] IPCC (Intergovernmental Panel on Climate Change), 2007. Climate Change 2007 – The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC, New York, Cambridge.

[14] Mannina, G., and Viviani, G. 2010. Water quality modelling for ephemeral rivers: Model development and parameter assessment. J. Hydrol. 393, 186–196.

[15] Nash, J.E. and Sutcliffe, J.V. 1970. River flow forecasting through conceptual models, J. Hydrol. 10, 282–290.

[16] Scheutz, C., Kjeldsen, P., Gentil, E., 2009. Greenhouse gases, radiative forcing, global warming potential and waste management – an introduction. Waste Management and Research 27, 716–723.

[17] Straub, W.A., Lynch, D.R. 1982. Models of landfill leaching. Moisture flow and inorganic strength", Journal of Environmental Engineering, 108, n.EE2, ASCE, April, 1982.