Environmental Science and Pollution Research (2018) 25:28169–28184
https://doi.org/10.1007/s11356-018-2844-y

RESEARCH ARTICLE

# Mathematical simulation to improve municipal solid waste leachate management: a closed landfill case

Ana López[1] · Tatiana Calero[1] · Amaya Lobo[1]

Received: 25 April 2018 / Accepted: 24 July 2018 / Published online: 2 August 2018


**Abstract**

This article presents an example of the application of simulation tools to estimate the post-closure evolution of leachate in a non-hazardous waste landfill. The objective of this work is to predict the behavior of leachate after the closure of the landfill for use as basic information with which to design the leachate management strategy in the following years. The MODUELO 4.0 mathematical landfill simulation software package was used for this purpose. The results of the simulation show that the concentrations in the leachate increase during the post-closure period, from values close to 2200 mg/L of COD and 1500 mg/L of $NH_4^+$ at the time of landfill closure to 3200 mg/L of COD and 5300 mg/L of $NH_4^+$ 20 years later. This increase is mainly due to the reduction in the flows, from 105 to 17 $m^3$/day on average, since the surface lining was installed. Consequently, pollutant fluxes decrease to values below 100 kg/day in both COD and $NH_4^+$ 3 months after closure. This evolution indicates that the management of this leachate will be simpler in the future, especially if it is co-treated with urban wastewater, as its contribution decreases. On the other hand, external water connections to the leachate collectors may cause a relevant increase in the volume of the global landfill effluent. Controlling runoff management and underground infiltrations could lead to important savings in leachate treatment during the aftercare phase.

**Keywords** Surface lining · Emissions · Modelling · Co-treatment · Ammonia · Chemical oxygen demand

## Introduction

Landfills are the first option in municipal solid waste management (MSWM) in many parts of the world (Laner et al. 2011; Morris and Barlaz 2011; Grisey and Aleya 2016) and their administration is an issue that extends over time, with environmental, technical, and economic dimensions (Wang et al. 2012). Landfill management involves intense monitoring of potential emissions, leachate and gas collection systems, receiving media (groundwater, surface water, soil and air), lining and final coverage for many years (Gibbons et al. 2014). According to the European Landfill Directive (European Council 1999) and the regulations of other countries, the owner of the landfill is financially responsible for its control for at least 30 years after operation has ended.

The characteristics of the disposed waste and the general state of the landfill change throughout the post-closure period, as do the needs for protection, maintenance and monitoring. Landfill operations and installations should be adapted at each stage of their lifespan. However, it is difficult to predict this evolution in detail and, for this reason, the usual practice is to adapt the elements to the progress of the changes that take place in the landfill.

Landfill simulation programs are able to anticipate future situations and can be a valuable aid for more efficient and sustainable management (Jianguo et al. 2010; Mishra and Karmakar 2018). They allow different scenarios to be analyzed in a faster, cheaper and more secure way than with the traditional methods of prototyping and experimentation (Denning 2000). Nowadays, a variety of models exist for the simulation of the main processes in landfills, that is,

Responsible editor: Marcus Schulz

✉ Ana López
lopezan@unican.es

Tatiana Calero
talcava@gmail.com

Amaya Lobo
loboa@unican.es

[1] Department of Water and Environment Sciences and Techniques, Environmental Engineering Group, University of Cantabria, Avda. De los Castros s/n, 39005 Santander, Cantabria, Spain

hydrology (Berger 2015), degradation (Gawande et al. 2010; Sanchez et al. 2010; Kamalan et al. 2011; Robqeck et al. 2011) and settlement (Babu et al. 2010). However, there are several simulation tools that integrate those processes and can therefore be used to help improve the design and operation of real facilities, such as the hydro-bio-mechanical (HBM) model (McDougall 2007), the landfill degradation and transport (LDAT) processes model (White et al. 2014) and MODUELO (Lobo and Tejero 2007a, b).

Among the elements to be controlled, the generation of leachate is a concern that continues throughout all the stages, right from the beginning of landfill operation. Several authors have shown that the contaminating content, and therefore the need for leachate management and treatment, depends on the composition of the landfill waste, the climatic conditions and the degree of decomposition of the waste (Slack et al. 2005; Renou et al. 2008; Schiopu and Gavrilescu 2010).

The leachate contaminants generated in non-hazardous waste landfills come largely from the decomposition of biodegradable waste, which results in organic matter dissolved into the leachate and is usually quantified through the chemical oxygen demand (COD) and the biological oxygen demand (BOD). A young leachate is highly biodegradable; it may present COD concentrations above 80,000 mg/L and BOD/COD ratios greater than 0.7 (Stegmann et al. 2005). It contains a high concentration of volatile fatty acids which causes the leachate to have a low pH value (Zhao et al. 2017). This acidic environment promotes an increasing concentration of metal species in leachate (Erses et al. 2005). Once the landfill has been closed, the waste stabilizes and the concentration of biodegradable compounds in the leachate tends to decrease, thus reducing the BOD/COD ratio to values below 0.2 (Stegmann et al. 2005). Numerous researchers have established that values lower than 0.1 in this relation correspond to an already stabilized landfill (Barlaz et al. 2002; Kjeldsen et al. 2002; Kalčíková et al. 2012; Gibbons et al. 2014; Ferraz et al. 2016). Most of the remaining organic materials are bio-refractory compounds, resulting in a moderately high level of COD, and pH within the alkaline range, which drives the metal species to a low level through the precipitation of metals (such as iron, zinc, etc.) and hydroxide (Zhao et al. 2017).

Another characteristic compound in municipal leachate is ammonium ($NH_4^+$). The $NH_4^+$ present in young leachate comes from the deamination of the amino acids during the destruction of the original organic compounds (Tatsi and Zouboulis 2002). In old leachate, however, the high presence of $NH_4^+$ is due to the hydrolysis and fermentation of the nitrogenous fractions of the biodegradable substrates (Carley and Mavinic 1990). A landfill can produce leachate with high concentrations of ammonium for more than 50 years after the installation of its surface lining (Chu et al. 1994). $NH_4^+$ remains stable under anaerobic conditions, accumulating in the leachate over time (Barlaz et al. 2002; Price et al. 2003), and may condition the end of the post-closure surveillance period (Kjeldsen et al. 2002; Price et al. 2003). The concentrations of $NH_4^+$ found in landfills by different authors vary from values below the limit of detection to values of 13,000 mg/L (Lo 1996).

Considering the variation in leachate characteristics over time, it seems reasonable to propose flexible treatment solutions that can be adapted at each stage. While, during the first years, treatment could be focused on biological processes to remove carbonaceous matter, perhaps over time the treatment should include an intensive physical-chemical treatment (Renou et al. 2008).

On the other hand, the reduction in the volume of leachate to be managed after the closure of the facilities must also be considered. When operation ends, the surface of the landfill is usually lined, which leads to significant reductions in the volume of leachate generated. At that stage, leachate management facilities could therefore be much smaller than during the operation period, and further decrease their size over time.

Therefore, to optimize landfill leachate management, it is essential to adjust the design to the needs of each moment throughout the lifetime of each facility. To perform this adjustment, it is necessary to have an estimate of the volume and pollution over a long period. Obtaining this estimate is a complex task, since it is influenced by a wide variety of local factors, such as those mentioned above.

This paper presents an example of analysis through mathematical simulation of the potential evolution of the leachate in a closed landfill. Based on a model developed using real operation and data collected by monitoring the facility under study, an estimate is obtained for the leachate volume and its organic contamination over time, which can be used as the base information with which to propose optimal solutions for its management, in terms of both size and typology. The following sections present the landfill that was studied, the simulation tool used, the model built and the simulation results obtained.

## Study site

The installation under study is a non-hazardous waste landfill in southern Europe, located in an area with a temperate (average annual temperature of 14 °C) and rainy climate (average annual precipitation of 1200 mm). Its operation began in 1988 and it was closed in September 2017 with a geomembrane capping. It occupies a surface area of around 92,000 m$^2$, with an approximate capacity of 125,000 m$^3$ and a height of 40 m.

The waste deposited in the landfill was mainly domestic mixed waste and, from 2007 onwards, residues from the bulk waste fraction of an MSWM system with selective collection of glass, paper and cardboard, and light packaging. Sewage sludge, street cleaning waste, industrial as well as household waste, construction and demolition waste, slag and foundry sands were also dumped there. The landfill operation period may be divided into three phases (Fig. 1).

In the course of the *first phase of operation*, waste was deposited in Sectors 1, 2, 3 and 4. This started in 1988, with municipal solid waste (MSW), construction waste, slag and inerts being received until the year 2000. The lining of the bottom and slopes was composed of compacted clay and earth. In the absence of a complementary geomembrane, groundwater and/or leachate may leak into the surroundings. The leachate collection system consists of a longitudinal drain in a fishbone pattern with its axis in Collector 1, which extends through Sectors 1, 2, 3 and 4.

The *intermediate phase of operation* began in 2001 and was lined in October 2012. During this phase, Sector 5 was completed. The residue was deposited in layers with a thickness of 3 m with intermediate 20-cm covers. With the use of a compactor-crusher machine, in this phase an overall average residue density of 1200 kg/m$^3$ was reached at the time of closure. The bottom lining was carried out in accordance with the European Landfill Directive (European Council 1999), including an impermeable geological barrier and a geomembrane. The leachate collection system also follows a fishbone pattern. Collector 2, a polyethylene pipe with a diameter of 200 mm, is located on the central axis, which extends throughout Sector 5 at an elevation of 100 m. This collector also receives, in its final stretch, the runoff generated on the surface of the facility from precipitation and collected through sewers. An automatic flowmeter was installed in the final section of Collector 2 for continuous monitoring, from 2009 to April 2012 (Fig. 2).

In the *last operation phase*, from November 2012 to November 2016, waste was deposited on the intermediate

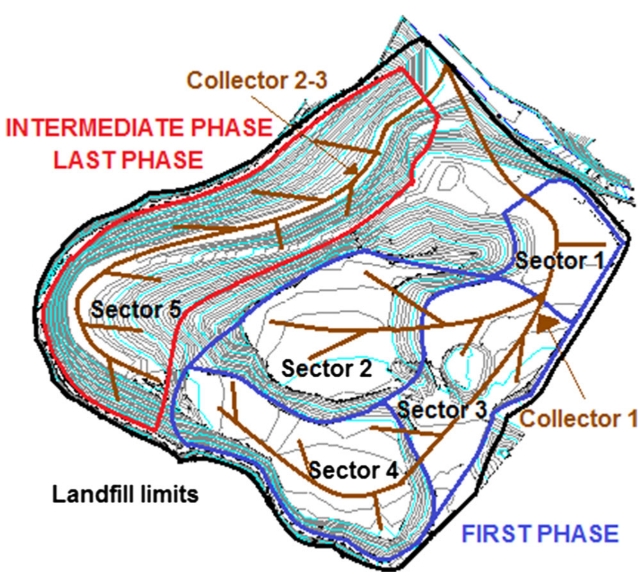


Fig. 1 Layout and operation phases in the landfill under study

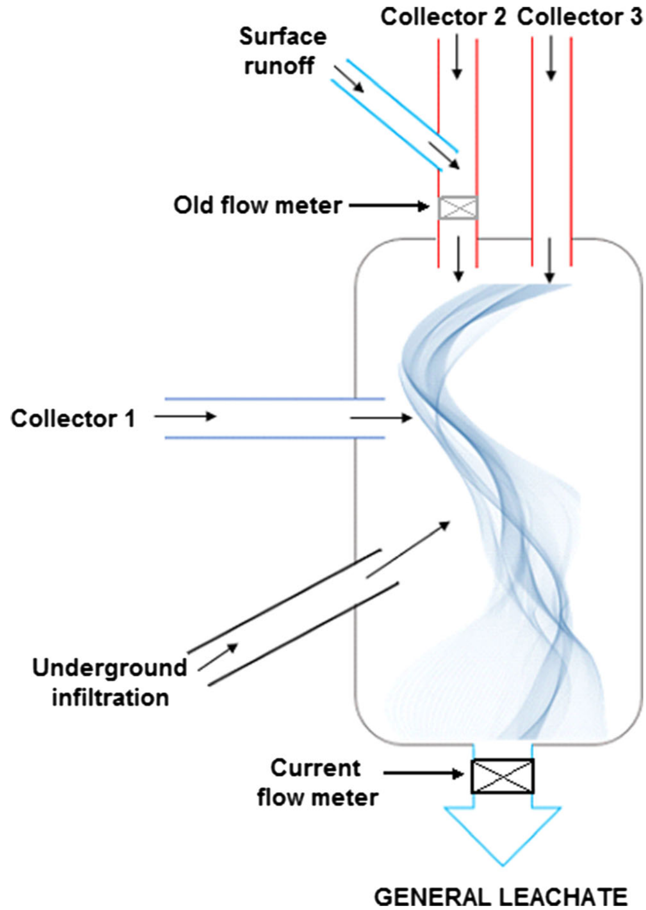


Fig. 2 Outline of the landfill leachate monitoring channel

phase, previously closed in compliance with the regulations established by Directive 1999/31/EC (European Council 1999) for the vertical expansion of landfills. The collection and evacuation of leachate is performed in a similar way to the previous phase, by means of a fishbone-patterned system of drainage. The central collector is Collector 3, a 250-mm diameter polyethylene pipe that also extends along Sector 5, at an elevation of 130 m.

The three collectors come together in a manhole in which the leachate from the three operation phases is mixed together with the volume of underground infiltrations that passes through part of the waste from the first operation phase and is collected by another pipe, as shown in Fig. 2. These latter flows contain some pollution, so they cannot be discharged directly into the river. The mixture of the leachate coming from Collectors 2 and 3 forms the "Pure Leachate," which together with the leachate conveyed by Collector 1, the rainwater collected as surface runoff and the underground infiltrations make up the "General Leachate." The flow of this final landfill effluent is continuously monitored by an automatic flowmeter installed since 2015. Previously, as of 2012, another flow measurement system was installed that presented several operational problems, such as the generation of foams in the channel, which distorted the measurements. This final landfill effluent is currently taken to the wastewater treatment plant (WWTP) of a nearby municipality where it is treated together with 8800 $m^3$/day of municipal wastewater, which presents average concentrations of 640 mg/L of COD and 45 mg/L of $NH_4^+$.

In order to ensure that the biological treatment process of the facility is not affected by the arrival of the leachate, loading limits of 1464 and 145 kg/day for COD and NH4+ were established, respectively. For other contaminants, no limitation has been established, as it has been proved that they do not affect the operation of the plant. Elements such as sulfates, chlorides, copper, zinc, manganese, arsenic and selenium have always been kept below 1000, 1600, 1, 3, 2, 0.1 and 0.1 mg/L, respectively, which are limit values of the integrated environmental authorization.

The co-treatment had worked well over the years the landfill was in operation but, with its forthcoming closure, there was a need to check whether future changes in the leachate and in particular in the problematic parameters, COD and NH4+, would require modification of the treatment conditions. This was the aim of the study described below.

## Methodology

### Simulation tool

The tool used for the simulation of the landfill was MODUELO. The program was developed on the basis of a review of existing models, adapting them to a three-dimensional representation of the landfill composed of layers made up of square horizontal section cells that are incorporated in accordance with the operational history of the landfill.

The first versions of MODUELO were described in detail in other papers (Lobo et al. 2002a, b; Lobo and Tejero 2007a). The latest version, MODUELO 4.0, includes the models of the third version but with improvements. It has been developed on the NET platform (Net Framework 3.5) with the Visual Studio 2008 Integrated Development Environment and the C# programming language (Cuartas 2012). With this version, the daily data on moisture in different areas of the landfill, the leachate volume and quality, the flows through the surrounding area, settlements, and quantity and quality of the gas that is generated can all be estimated.

Figure 3 shows a simplified diagram of the general algorithm of the program. The user enters data about the landfill morphology, form of operation, local meteorological conditions and the characteristics of the landfilled waste. With this information, the program simulates the growth and operation of the landfill over time, the hydrological phenomena on the surface and within the waste, its biodegradation, and its settlement by compaction and degradation. As a result, the evolution of the landfill can be analyzed throughout its lifespan. Time series of global variables are obtained, such as the volume of the waste dumped, its total moisture content, the volume and quality of the leachate, the volume and composition of the gas or the average settlement of waste (Cuartas et al. 2018).

Since it was created in 1998, MODUELO has been applied to theoretical cases, laboratory tests and real installations and its usefulness has been demonstrated with satisfactory results (López et al. 2008; Lobo et al. 2011; Cuartas et al. 2018).

## Landfill model

### Model definition

Building a detailed model requires having real data available with which to generate the terrain, the waste generation and the meteorological models. The greatest source of contamination in the landfill nowadays is Sector 5; Collector 1, which serves the oldest area, is estimated to contribute only 5% of the General Leachate flow. For this reason, the landfill model was created including only the intermediate and final operation phases, as they were the ones for which sufficiently detailed information was available.

The *waste generation model* was created from the landfill waste input records (see Fig. 4) from 2001 to November 2016, where entries were classified by place of origin. The waste characterization data in 2007, 2012 and 2016 provided by the MSWM Regional Agency, as well as the provincial Integrated Municipal Waste Management Plan 2002–2016, were used to establish the composition of the waste.

The *meteorological model* was constructed with data recorded from 2001 to 2017 using daily mean values of temperature (°C), relative humidity (%) and wind speed (km/h). Daily solar radiation data (watt/$m^2$), number of hours of sunlight (h) as well as hourly precipitation (mm) in the landfill were also taken into account. Some of this data was not available at the landfill weather station, so figures from several nearby stations were used. The triangulation technique was applied to approximate the missing data.

MODUELO recreates the placement of the cells in the order indicated by the user according to the available information. For the construction of the *terrain model*, landfill topographic surveys, from 2001 to 2016, were used. The original topographic information that was available was used to model the dumping vessel. Then, it was filled according to the dumping sequence over time, so that the landfill was finally represented in MODUELO by 4168 cells (3 m thick and a surface area of 10 × 10 m). They were distributed as follows:

- 15 "SOIL CELLS," which represent the frontal slope of the dumping vessel.
- 3753 "LANDFILL" cells that represent the buried waste with their corresponding intermediate cover.

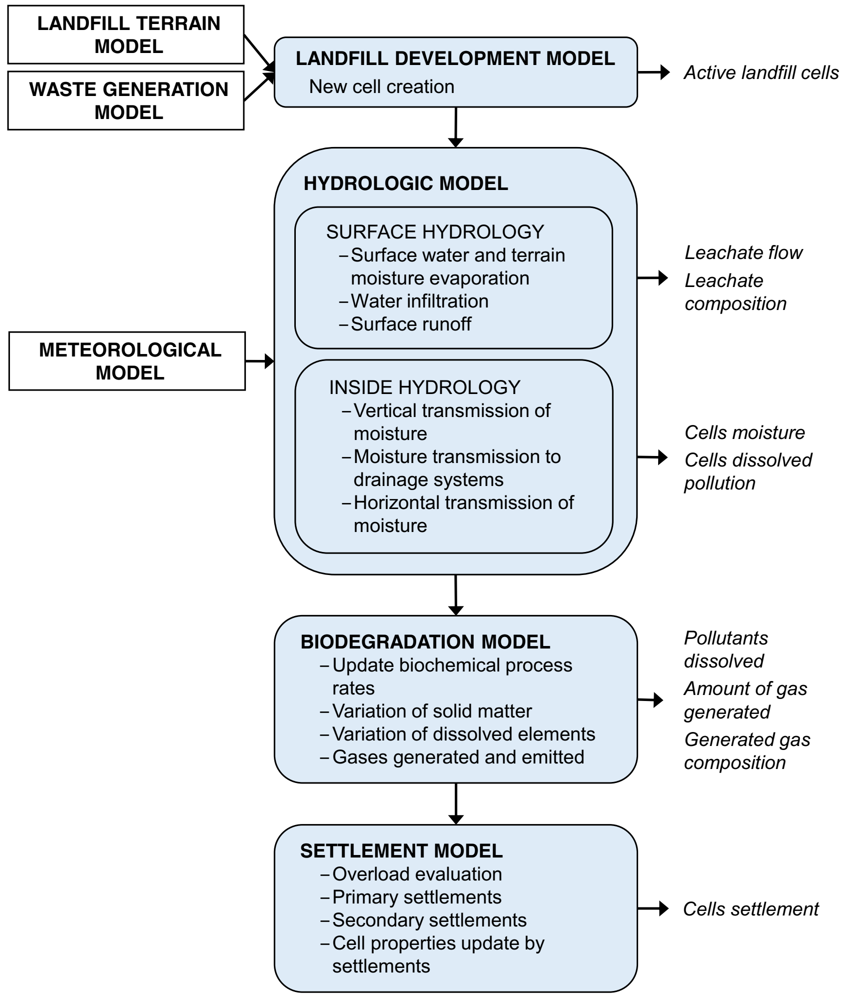


**Fig. 3** Scheme of the general calculation algorithm of the MODUELO program

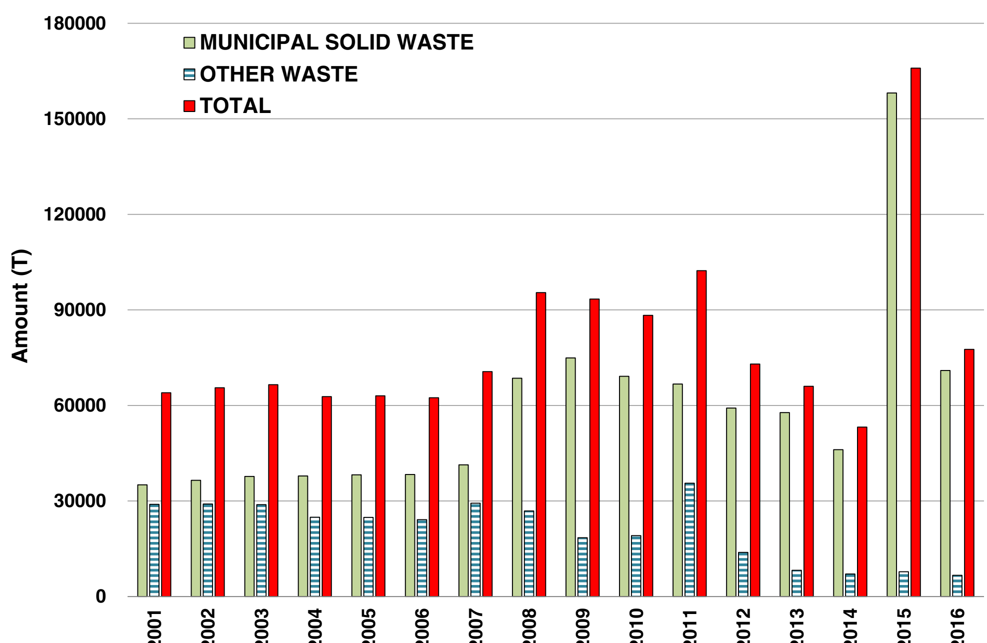


**Fig. 4** Waste disposed of in the landfill since 2001

– 400 "LINED LANDFILL" cells which represent the last layer of the second operation phase and its lining.

In addition, 512 "LINING CELLS" were used to represent the final cover of the landfill.

In this way, the waste model consists of 1,050,840 m$^3$ of waste (984,637 t), included in the LANDFILL cells, and 112,000 m$^3$ of waste (104,944 t) included in the LINED LANDFILL cells. Table 1 shows the hydrological characteristics assigned to the landfill cells.

To simulate the characteristics of the different waste, 62 generation periods with different properties were created, which cover all the simulated operation phases. The global composition of the waste dumped, as well as the main characteristics of the components considered, is summarized in Table 2 (Cuartas 2012). Since slag and sand were included as covering material, they do not appear as a specific waste entry.

## Model calibration

Once the model had been constructed, first the hydrological model and then the biodegradation model were calibrated and validated. The information provided by the landfill operator company about leachate flow and pollutants concentration was used for this purpose. It included the following data:

**Table 1** Hydrological characteristics assigned to the model landfill cells

| Waste characteristics | LANDFILL cell | LINED LANDFILL cell | References |
|---|---|---|---|
| Initial residual moisture (% wet weight) | 10 | 10 | (Schroeder et al. 1994) (Tchobanoglous et al. 1993) |
| Initial field capacity (% wet weight) | 25 | 25 | (Schroeder et al. 1994) (Tchobanoglous et al. 1993) |
| Initial saturation moisture (% wet weight) | 40 | 40 | (Schroeder et al. 1994) (Tchobanoglous et al. 1993) |
| Initial vertical hydraulic conductivity (m/s) | 0.00001 | 0.00001 | (Koda and Zakowicz 1999), (Oweis et al. 1990), (Schroeder et al. 1994) |
| Initial horizontal hydraulic conductivity (m/s) | 0.00001 | 0.00001 | (Koda and Zakowicz 1999), (Oweis et al. 1990), (Schroeder et al. 1994) |
| Cover characteristics | LANDFILL cell | LINED LANDFILL cell | References |
| Cover thickness (m) | 0.2 | 0.2 | Operation data |
| Initial moisture content (% wet weight) | 10 | 10 | (Schroeder et al. 1994) (Tchobanoglous et al. 1993) |
| Initial density (kg/m$^3$ wet weight) | 1960 | 1960 | Operation data |
| Initial residual moisture (% wet weight) | 1 | 1 | (Schroeder et al. 1994) (Tchobanoglous et al. 1993) |
| Initial field capacity (% wet weight) | 6 | 6 | (Schroeder et al. 1994) (Tchobanoglous et al. 1993) |
| Initial saturation moisture (% wet weight) | 20 | 20 | (Schroeder et al. 1994) (Tchobanoglous et al. 1993) |
| Initial vertical hydraulic conductivity (m/s) | 0.00001 | $10^{-10}$ | (Schroeder et al. 1994) |
| Surface infiltration model | LANDFILL cell | LINED LANDFILL cell | References |
| Minimum infiltration rate (mm/h) | 10 | 0 | (Huber and Dickinson 1988) |
| Maximum infiltration rate (mm/h) | 76.2 | 0 | (Huber and Dickinson 1988) |
| Horton parameter (1/h) | 4.14 | 4.14 | (Huber and Dickinson 1988) |
| Evapotranspiration model | LANDFILL cell | LINED LANDFILL cell | References |
| Evaporation depth (m) | 0.15 | 0 | (Schroeder et al. 1994) |
| Wilting point (% of residual moisture) | 100 | 100 | (Schroeder et al. 1994) |
| Runoff model | LANDFILL cell | LINED LANDFILL cell | References |
| Maximum surface accumulation (m) | 0.15 | 0.15 | (Huber and Dickinson 1988) |
| Preferential flow model | LANDFILL cell | LINED LANDFILL cell | References |
| Fraction of volume affected by preferential channels (%) | 45 | 45 | (Rosqvist and Destouni 2000) |
| Ratio preferential/homogeneous flow hydraulic conductivity | 100 | 100 | (Rosqvist and Destouni 2000) |

**Table 2** Global composition of landfilled waste and principal characteristics of the materials included

| Components | Dumped waste composition (% wet weight) | C | H | O | N | S | Ashes | Biodegradability | Biodegradable fraction (%) | Moisture (% wet weight) |
|---|---|---|---|---|---|---|---|---|---|---|
| Bricks | 1.0 | 50.0 | 7.3 | 33.5 | 0.2 | 0.2 | 8.8 | Inert | 0 | 2 |
| Inert | 2.6 | 26.3 | 3.0 | 2.0 | 0.5 | 0.2 | 68.0 | Inert | 0 | 3 |
| Wood | 1.8 | 49.5 | 6.0 | 42.7 | 0.2 | 0.1 | 1.5 | Slowly | 17 | 20 |
| Metal | 3.0 | 4.5 | 0.6 | 4.3 | 0.1 | 0.0 | 90.5 | Inert | 0 | 2 |
| Nappies and cellulose | 11.9 | 44.5 | 6.0 | 49.5 | 0.0 | 0.0 | 0.0 | Inert | 0 | 20 |
| Paper-cardboard | 11.2 | 43.7 | 6.0 | 44.3 | 0.3 | 0.2 | 5.5 | Readily | 41 | 6 |
| Plastic | 12.8 | 60.0 | 7.2 | 22.8 | 0.0 | 0.0 | 10.0 | Inert | 0 | 6 |
| Food waste | 36.3 | 48.0 | 6.4 | 37.6 | 2.6 | 0.4 | 5.0 | Readily | 64 | 70 |
| Garden waste | 2.1 | 47.8 | 6.0 | 38.0 | 3.4 | 0.3 | 4.5 | Slowly | 35 | 60 |
| Textile | 5.7 | 55.0 | 6.6 | 31.2 | 4.6 | 0.2 | 2.4 | Slowly | 32 | 4 |
| Glass | 4.5 | 0.5 | 0.1 | 0.4 | 0.1 | 0.0 | 98.9 | Inert | 0 | 2 |
| Urban sludge | 7.0 | 28.0 | 5.0 | 12.0 | 5.0 | 2.0 | 48.0 | Readily | 40 | 75 |

– Series of daily flow measured manually in Collector 2 from 2005 to 2008.
– Daily records of the flowmeter in Collector 2 from 2009 to April 2012.
– Daily records of the flowmeter for the General Leachate from 2015 to 2017.
– Estimations of the average underground flow based on several spot measurement campaigns since 2015: 81 $m^3$/day in dry weather periods and 115 $m^3$/day in rainy weather conditions.
– Estimations of the contribution of Collector 1 based on several spot measurement campaigns since 2015: 5% of the General Leachate.
– Estimation of the contribution of surface runoff to Collector 2: 70% of the precipitation on the whole surface of the landfill facilities.
– Analytical data, obtained in the regular monitoring procedures from monthly spot samples of the leachate, including:

- Collector 2 series: COD and $NH_4^+$ leachate concentration from February 2002 to May 2009.
- General Leachate series: COD and $NH_4^+$ concentration from 2008 to 2017.

In addition, a specific campaign for characterizing the different water sources that make up the General Leachate was carried

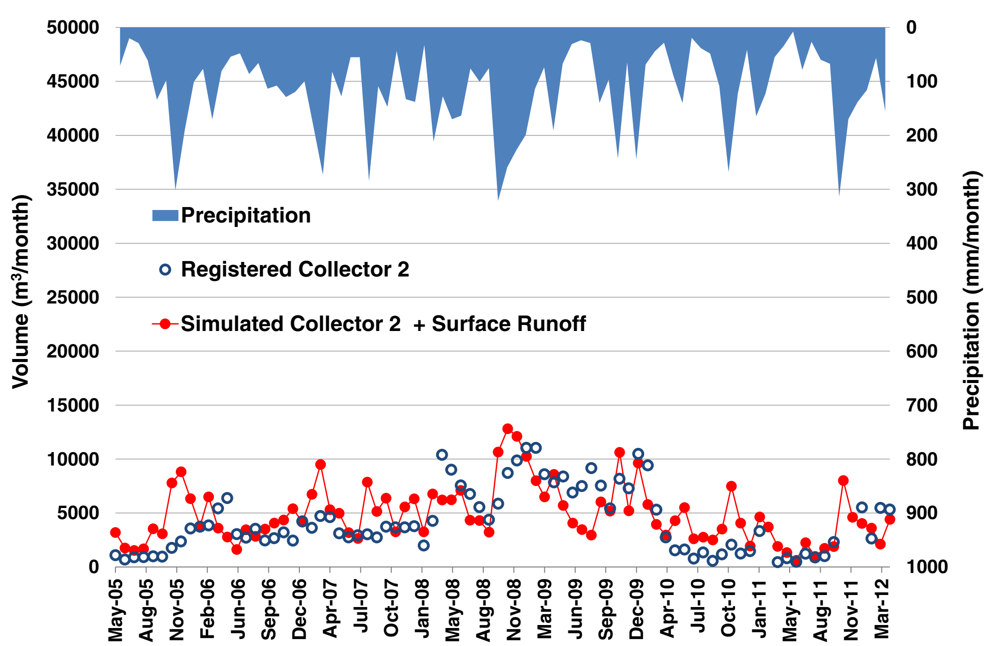


**Fig. 5** Monthly leachate volume measured and simulated for Collector 2 in the period 2005–2012

out for this study to measure COD and $NH_4^+$ concentrations from October 2016 to March 2017 in the leachate of Collector 1, Collector 2, Collector 3 and Underground Infiltrations.

The analytical series of the regular monitoring also included other parameters that were not considered in the work, since they do not threaten the treatment in this case: sulfates, chlorides, aluminum, iron, manganese, arsenic, cadmium, copper, chromium, nickel, lead, zinc, total phosphorus, conductivity, suspended solids, pH, color, toxicity, bicarbonates, anionic surfactants, fluorides, selenium and sometimes nitrates, nitrites and Kjeldahl nitrogen.

The calibration was performed by fitting the simulation results to the data measured during the intermediate phase of operation, in Collector 2. Subsequently, the calibrated parameters were validated by contrasting the simulation results during the last operation phase with the available data measured for the General Leachate, since 2015. In this latter period, the simulation results include the values given by the landfill operators for the underground infiltration flows and the volume discharged by Collector 1. The relative average deviation (RAD) was used as a measure of the fitting error.

The hydrological calibration parameters were the infiltration velocity, the waste hydraulic conductivity and the fraction of waste volume affected by preferential channels. The resulting values are shown in Table 1.

Figure 5 shows the distribution of the simulated leachate flow compared with that registered during the calibration period (RAD 0%). The total simulated leachate volume in Collector 2 during this period (407,262 $m^3$) also closely matched the measured value (407,927 $m^3$).

Figure 6 presents the comparison of monthly volumes in the General Leachate for the validation period (RAD − 2%). Table 3 shows the annual volume of General Leachate registered compared with the simulated results during the validation years.

**Table 3** Comparison of the General Leachate volume measured with the simulated flows in 2015–2017

| Year | Registered General Leachate ($m^3$) | Simulated General Leachate ($m^3$) | Absolute relative deviation (%) |
|---|---|---|---|
| 2015 | 111,830 | 123,730 | 11 |
| 2016 | 126,938 | 126,566 | 0 |
| 2017 | 108,478 | 103,813 | 4 |
| Total | 347,246 | 354,110 | 2 |

The degradation model was calibrated with the leachate quality data from Collector 2, for the same period as the hydrological model. The data to fit were COD and $NH_4^+$ concentration and load. The slow and ready rates of hydrolysis were determined first by adjusting the measured concentration series of $NH_4^+$. Then, the rates of acetogenesis and acetoclastic methanogenesis and the dragging factor were calibrated together, by adjusting the COD series. Both the hydrogenophilic methanogenesis rate and the accessibility factor ($f_{ac}$) were taken as constant due to the lack of sufficient information to determine them. Their values were chosen based on the results from other simulations (Lobo and Tejero 2007b; López et al. 2009, 2012). Table 4 summarizes the parameter values resulting from the calibration.

Figure 7 shows the simulation results compared to the analytical data of Collector 2 leachate, which present a RAD of − 44% in COD and 15% in $NH_4^+$. The calibration results were validated with the measured data available for Collector 3 (see Fig. 8). The RAD

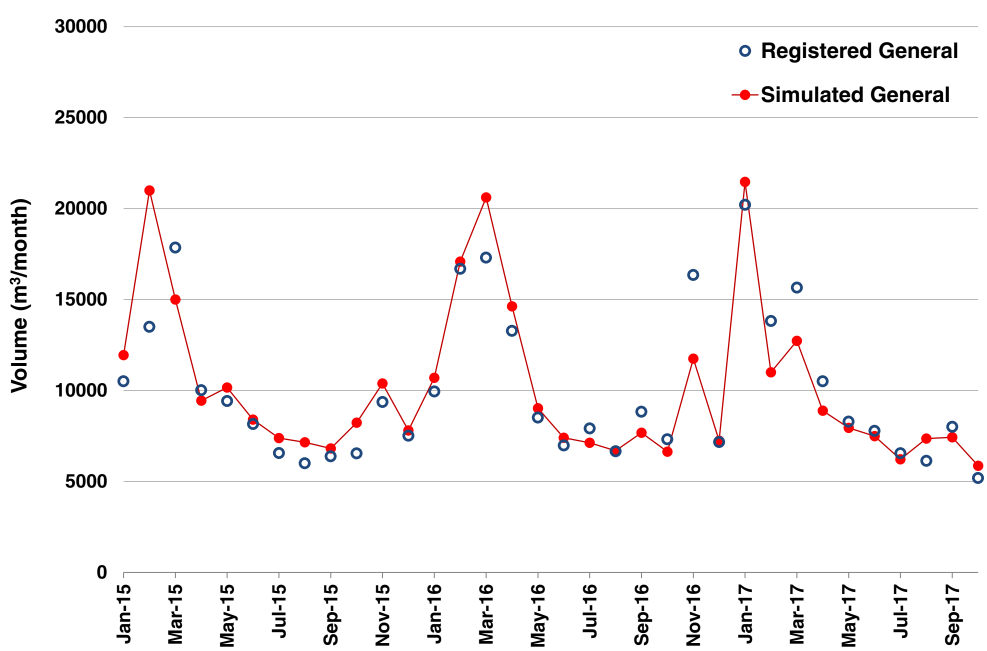


**Fig. 6** Measured and simulated monthly volume for General Leachate

**Table 4** Parameters resulting from the calibration of the degradation model

| Parameter | | Adopted value | Reference |
|---|---|---|---|
| Ready hydrolysis rate | $kh_{rea}$ (day$^{-1}$) | 0.0006 | 0.00023–0.05 |
| Slow hydrolysis rate | $kh_{slo}$ (day$^{-1}$) | 0.00006 | 0.00003–0.0025 |
| Acetogenesis rate | $k_{AC}$ (day$^{-1}$) | 0.05 | 0.005–0.1 |
| Acetoclastic methanogenesis rate | $k_A$ (day$^{-1}$) | 0.05 | 0.005–0.7 |
| Hydrogenophilic methanogenesis rate | $k_{H2}$ (day$^{-1}$) | 50 | 50–500 |
| Dragging factor | $f_{ar}$ | 0.01 | 0.01–0.5 |

obtained for that period was 51 and 24% in COD and $NH_4^+$, respectively. In addition, the total $NH_4^+$ load data provided by the landfill management company were also checked, as shown in Fig. 9 (RAD −2%).

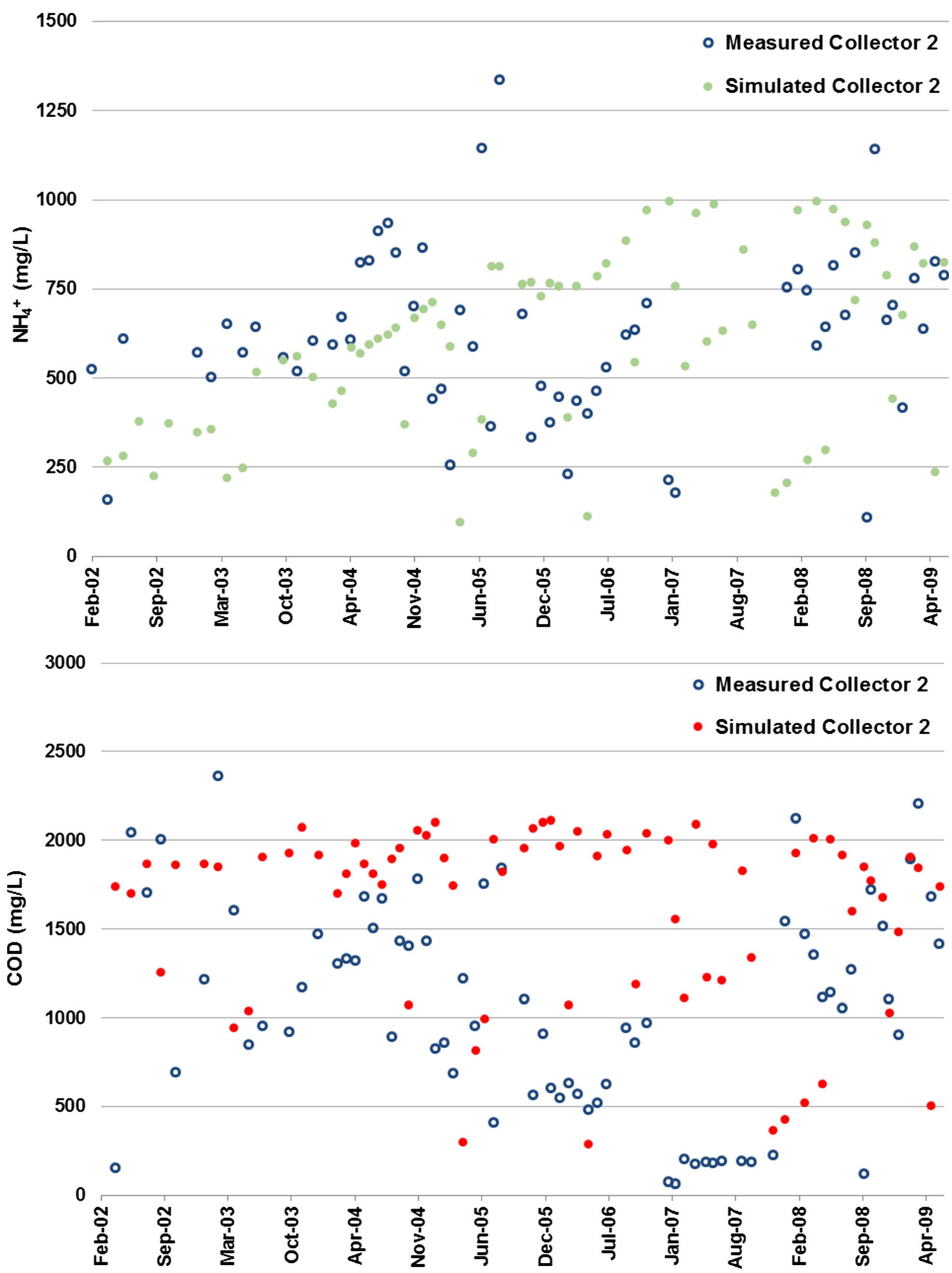


**Fig. 7** Measured and simulated $NH_4^+$ and COD leachate concentrations for Collector 2 during the calibration period

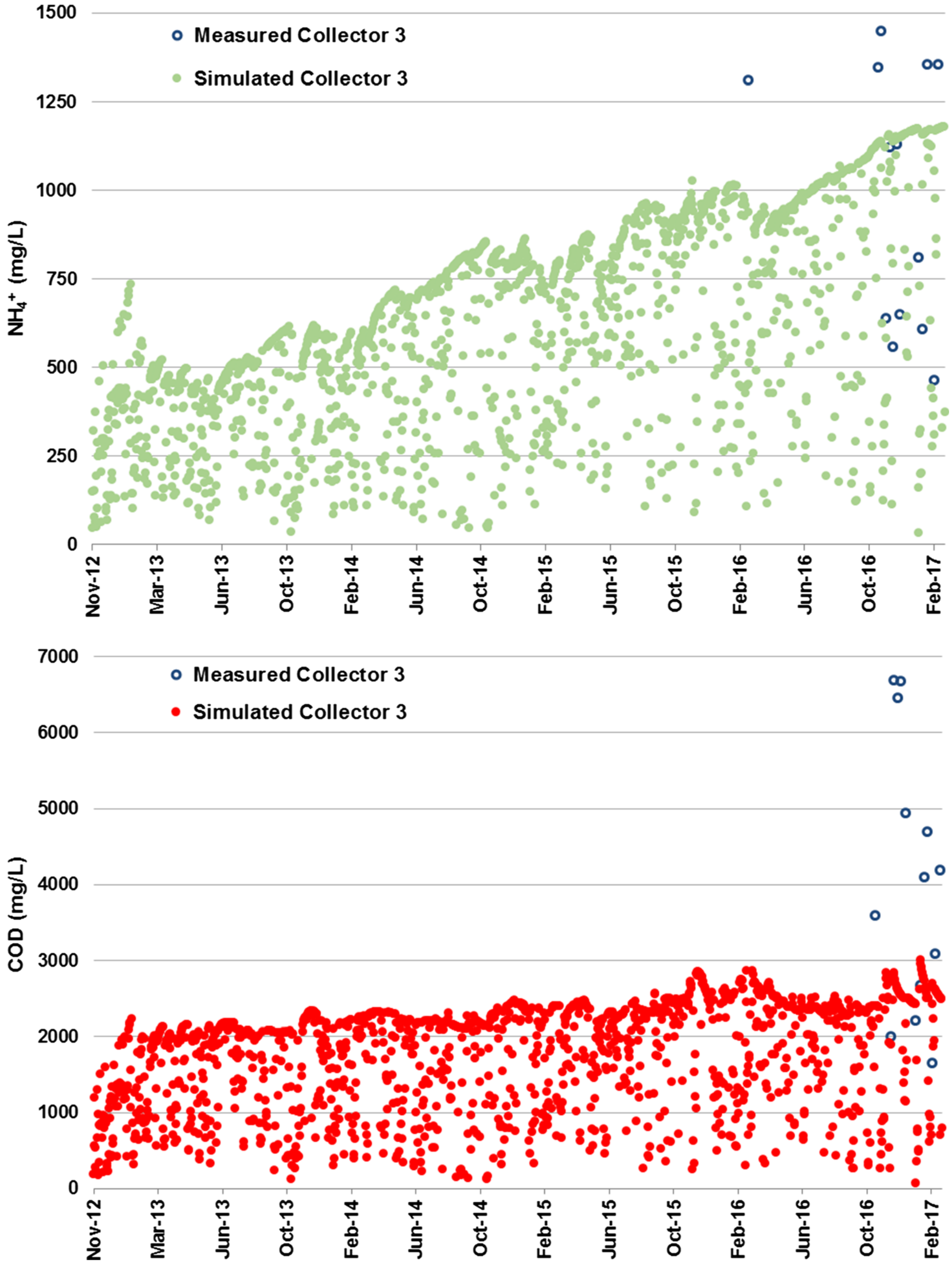


**Fig. 8** Measured and simulated $NH_4^+$ and COD leachate concentration for Collector 3 during the validation period

## Results and discussion

### Leachate volume

A 20-year simulation was carried out with the calibrated model, until 2037.

Figure 10 shows the evolution of the Pure Leachate production (from Collectors 2 and 3) throughout the study period as well as this volume plus the surface runoff and underground infiltrations that were collected. The graph shows that, as a result of the surface lining, the volume of the Pure Leachate falls between 2017 and 2018 by more than 80%, from an average volume of 105 $m^3$/day in 2017 to 17 $m^3$/day in 2018. This decrease is one of the reasons for the geomembrane coverage (Hullings 2017). In case of breakage due to an accident or aging of the lining, the volumes of Pure Leachate could be reactivated a few years later. However, several authors indicate that this type of covering has an extensive durability, between 55 and 120 years (Rowe and Islam 2009; Benson et al. 2011). Figure 10 shows that the largest contribution to the General Leachate since 2018, 1 year after closure, comes from both the surface runoff and the underground infiltrations that are intercepted.

Table 5 shows the annual volume of each component of the General Leachate in four different years, to highlight the

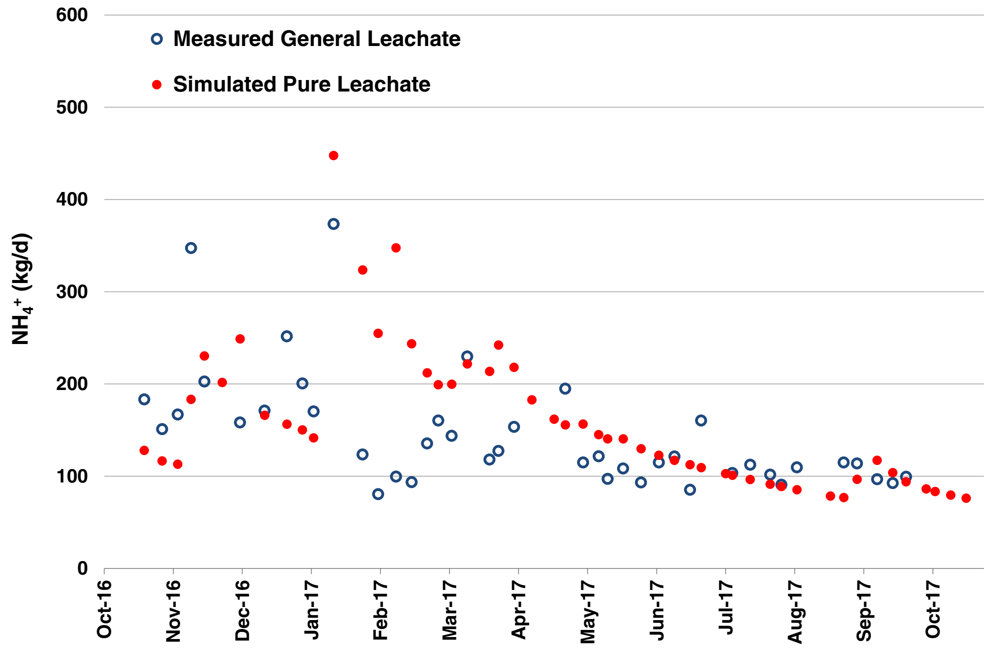


**Fig. 9** Comparison between $NH_4^+$ loads of the General Leachate and simulated Pure Leachate

tendency of leachate volume over time. Since the landfill closure, the Pure Leachate volume decreases and the underground infiltrations and surface runoff become more relevant, reaching 47 and 51% of the total General Leachate volume, respectively, after 10 years. The volume contributed to the General Leachate by the sources other than the "Pure Leachate" is expected to stay within ranges similar to those of recent years, since the flow collected from surface runoff depends directly on the precipitation that falls during the year and the total volume contributed by the underground infiltrations is approximately constant every year, with slight variations according to the precipitation.

## Leachate contamination

Figure 11 shows how concentrations of COD and $NH_4^+$ in the Pure Leachate will increase in the coming years, reaching values above 3000 mg/L in COD and 5000 mg/L in $NH_4^+$ 20 years after closure. This increase is mainly due to the drastic decrease in the volume of leachate generated after the surface lining has been installed. In addition, despite the interruption of surface water infiltration, the waste still has sufficient moisture to continue degrading and dissolving matter and therefore the concentrations remain high. As the

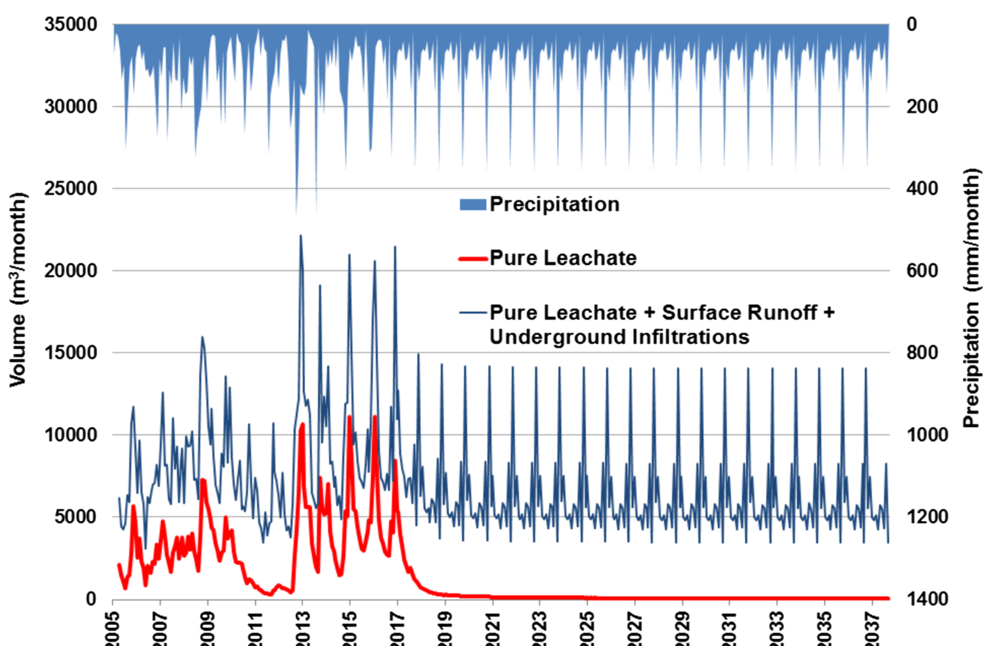


**Fig. 10** Evolution of the leachate flows during the years considered in the study

**Table 5** Annual volume estimated for the General Leachate components

| Source | 2016 | 2017 | 2027 | 2037 |
|---|---|---|---|---|
| Collector 2 ($m^3$) | 14,451 | 10,620 | 586 | 319 |
| Collector 3 ($m^3$) | 45,725 | 27,686 | 352 | 111 |
| Surface runoff ($m^3$) | 30,012 | 37,056 | 37,952 | 37,952 |
| Underground infiltrations + Collector 1 ($m^3$) | | | 35,107 | 35,107 |
| General Leachate ($m^3$) | 126,938 | 108,478 | 73,997 | 73,489 |

landfill dries up in the long term, the reactions will stop and therefore the amount of pollution emitted will also drop.

In contrast, the General Leachate, because it is diluted by the volume of surface runoff, intercepted underground infiltrations and Collector 1, will present significantly lower concentrations, not exceeding 150 mg/L in COD and $NH_4^+$.

Table 6 shows the simulated annual average concentration of $NH_4^+$ and COD and BOD/COD ratio at different times in the simulation, for the Pure and General Leachate. The results indicate that the Pure Leachate concentrations will increase in the simulation period by 40% in COD and by 260% in the case of $NH_4^+$. In contrast, the concentrations in the General Leachate will decrease in that period by 89 and 82% for COD and $NH_4^+$, respectively.

As shown in Fig. 12, the load behavior for both contaminants is very similar. The maximum release occurs in early 2017 and thereafter the load is significantly reduced. The release of contaminants decreases drastically after lining, descending from 375 kg/day of $NH_4^+$ and 950 kg/day of COD at the beginning of 2016 to less than 100 kg/day at the end of 2017 in both contaminants. The release curves of the Pure Leachate and General Leachate are very similar, since the main source of contamination of the General Leachate is Pure Leachate.

## Comparison with other cases

The concentrations obtained for $NH_4^+$ are similar to those found by Di Palma et al. (2002) (3917 mg/L), Wu et al. (2004) (5500 mg/L) and Lopez et al. (2004) (5210 mg/L), but much higher than those observed by Lou et al. (2009) (1388 mg/L in an 11-year leachate), Fan et al. (2006) (190 mg/L in a 12-year leachate), Ferraz et al. (2014) (800 mg/L in a 22-year leachate) and Zhao et al. (2017) (492 mg/L in a 30-year leachate).

According to Stegmann et al. (2005), the COD concentration expected for the Pure Leachate after closure is in the range of the reference values for the methanogenic phase (460–8300 mg/L). It also coincides with the limit proposed by Renou et al. (2008) for an old landfill, since COD concentrations remain below 4000 mg/L throughout the simulated period.

The evolution of the estimated COD concentration is within the range found by Fan et al. (2006) in a 12-year landfill (4210–840 mg/L) and somewhat higher than that found in a 17-year landfill (1340–320 mg/L). However, numerous authors have found higher concentrations than those obtained in this work in landfills classified as mature, such as Ferraz et al. (2014) (4860–4425 mg/L in a 22-year leachate), Lopez

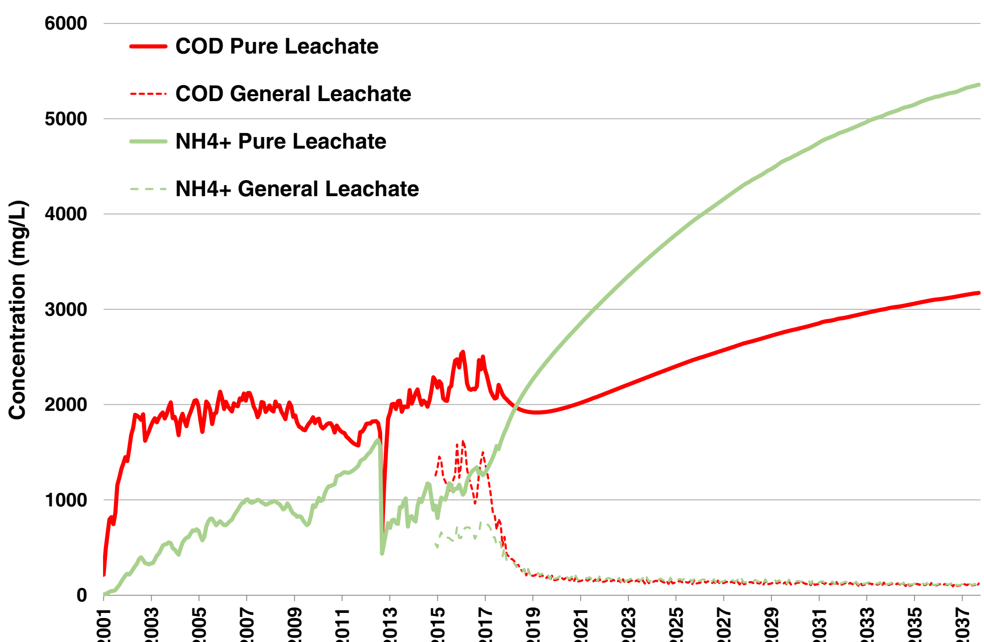


**Fig. 11** Estimation of the monthly average $NH_4^+$ and COD concentrations of the leachate

**Table 6** Annual average concentrations of COD and $NH_4^+$, and BOD/COD ratio estimated for the leachate

| | Contaminant | 2016 | 2017 | 2027 | 2037 |
|---|---|---|---|---|---|
| Pure Leachate | COD (mg/L) | 2315 | 2194 | 2596 | 3154 |
| | BOD/COD | 0.71 | 0.63 | 0.07 | 0.03 |
| | $NH_4^+$ (mg/L) | 1222 | 1467 | 4209 | 5325 |
| General Leachate | COD (mg/L) | 1270 | 962 | 132 | 107 |
| | $NH_4^+$ (mg/L) | 667 | 620 | 151 | 113 |

et al. (2004) (10,540 mg/L), Anfruns et al. (2013) (6200 mg/L) or Ganigué et al. (2007) (6100–3200 mg/L).

The decrease in the BOD/COD ratio is attributed to the consumption of the biodegradable material in the first years, leaving the non-biodegradable recalcitrant compounds in the leachate (Renou et al. 2008). According to Stegmann et al. (2005), from 2021 onwards, the leachate could be considered stabilized, in the methanogenic phase, since it will present BOD/COD values lower than 0.2.

When the dilution that occurs in the General Leachate is considered, the evolution of the concentrations is very different. In this case, the concentration of $NH_4^+$ decreases significantly over time in the same way as that found by Ziyang et al. (2009) in their study on the characteristics of a leachate at different years ($NH_4^+$ went from 4251 mg/L in a 2-year leachate to 238 mg/L with 12 years, while COD went from 7125 to 695 mg/L in the same period).

The general concentrations of $NH_4^+$ and COD obtained in this work 10 years after closure are in agreement with the concentrations found by Kalčíková et al. (2012) (55 mg/L of $NH_4^+$ and 117 mg/L of COD) in an old landfill that received waste for 20 years. In addition, the General Leachate could also be classified as mature according to the classification proposed by Kamaruddin et al. (2017), who proposed ranges for $NH_4^+$ (20–900 mg/L) and COD (100–2800 mg/L).

## Implications in co-treatment

Co-treatment is precisely one of the options indicated to overcome the difficulties involved in treating old leachates (Ferraz et al. 2016). In fact, the concentration of $NH_4^+$ obtained in the simulation shows that difficulties could arise for a separate biological treatment of the Pure Leachate, since it reaches 1500 mg/L from the year of closure onwards (Lou et al. 2009). Even the growth of microorganisms could be inhibited in the treatment processes as of 2021, when they exceed 3000 mg/L (Lou et al. 2009). In this case, the leachate could require a pre-treatment before mixing with wastewater (Yuan et al. 2016). However, in the year of closure, the volume of Pure Leachate is less than 2% of the total flow to be treated, and therefore, its impact on the whole is minimal.

Given these limitations, the current mixture of Pure Leachate with streams that dilute it would facilitate its biological purification, which could be carried out even without mixing it with municipal wastewater.

On the other hand, if the purification process is analyzed, the impact of the leachate is produced by the pollutant load rather than by the concentration of the liquid itself. In the case studied, the admission limits required by the treatment plant are 145 kg/day for $NH_4^+$ and 1464 kg/day for COD. According to the results obtained, these loads will not be exceeded in the post-closure years: the leachate will have an average load of 34 kg/day of $NH_4^+$ and COD in 2018, which will decrease in subsequent years. This fact implies that reducing the dilution of the

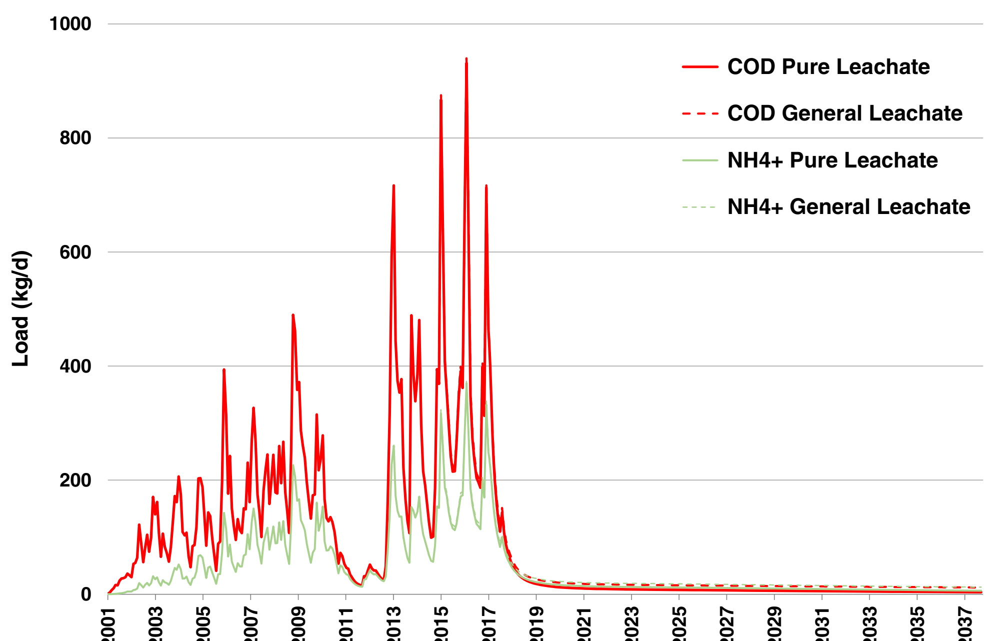


**Fig. 12** Estimation of the monthly average load of $NH_4^+$ and COD in the Pure and General Leachate

leachate (by disconnecting, for example, surface runoff water) would not impair the treatment, although it would entail an increase in the input concentrations.

## Conclusions

This work presents an example of how, even when the available data present some uncertainties, modelling tools may be used to generate information that can be helpful when it comes to making decisions on landfill operation with reduced economic and time costs.

The evolution of leachate characteristics in a closed municipal landfill has been studied through mathematical simulations, based on available field data. The results obtained make it possible to evaluate a priori the options for leachate treatment over the next 20 years, after closure of the landfill.

The case studied here highlights the need to consider different periods throughout the lifespan of a landfill. The relevant changes that occur after closure can lead to a drastic reduction in leachate volume and, moreover, to pollutant concentrations that limit its treatment.

The results for the landfill studied here show a rapid descent of the Pure Leachate flow, so that in 1 year the collected volume will represent less than 10% of the volume collected before surface lining. At the same time, the concentrations of pollutants will increase significantly, to values that could endanger a biological treatment of the leachate alone. However, if the contribution of underground infiltration and surface runoff is maintained, the General Leachate flow will remain at approximately 68% of the current value, before lining. As a consequence, although the Pure Leachate concentrations increase throughout the simulated period, dilution by external water entries means a significant reduction in the concentrations in the General Leachate for the described case.

On the other hand, the results obtained in this work highlight the fact that other decisions, besides surface lining, may have a great impact on the costs of post-closure leachate management. The surface runoff and underground infiltrations collected with the leachate may account for a large part of the total flow to be treated before discharge (more than 50% in the case described here). These flows usually present much lower pollution than leachate, and could even be discharged directly into the natural environment in some cases. Therefore, collecting and conveying these flows separately could lead to significant savings in treatment.

## References

Anfruns A, Gabarró J, Gonzalez-Olmos R, Puig S, Balaguer MD, Colprim J (2013) Coupling anammox and advanced oxidation-based technologies for mature landfill leachate treatment. J Hazard Mater 258–259:27–34. https://doi.org/10.1016/j.jhazmat.2013.04.027

Babu GLS, Reddy KR, Chouskey SK, Kulkarni HS (2010) Prediction of long-term municipal solid waste landfill settlement using constitutive model. Pract Period Hazard Toxic Radioact Waste Manag 14:139–150. https://doi.org/10.1061/(ASCE)HZ.1944-8376.0000024

Barlaz MA, Rooker AP, Kjeldsen P, Gabr MA, Borden RC (2002) Critical evaluation of factors required to terminate the postclosure monitoring period at solid waste landfills. Environ Sci Technol 36:3457–3464. https://doi.org/10.1021/es011245u

Benson CH, Albright WH, Fratta DO et al (2011) Engineered covers for waste containment: changes in engineering properties and implications for long-term performance assessment Office of Nuclear Regulatory Research. Washington, D.C.

Berger KU (2015) On the current state of the hydrologic evaluation of landfill performance (HELP) model. Waste Manag 38:201–209. https://doi.org/10.1016/j.wasman.2015.01.013

Carley BN, Mavinic DS (1990) The effects of external carbon loading on nitrification and denitrification of a high-ammonia landfill leachate. Res J Water Pollut Control Fed 63:51–59

Chu LM, Cheung KC, Wong MH (1994) Variations in the chemical properties of landfill leachate. Environ Manag 18:105–117. https://doi.org/10.1007/BF02393753

Cuartas M (2012) Optimización del diseño de vertederos de residuos sólidos basada en modelización. Ph.D.Thesis, University of Cantabria, Spain

Cuartas M, López A, Pérez F, Lobo A (2018) Analysis of landfill design variables based on scientific computing. Waste Manag 71:287–300. https://doi.org/10.1016/j.wasman.2017.10.043

Denning PJ (2000) Computer science: the discipline. In: Encyclopedia of Computer Science

Di Palma L, Ferrantelli P, Merli C, Petrucci E (2002) Treatment of industrial landfill leachate by means of evaporation and reverse osmosis. Waste Manag 22:951–955. https://doi.org/10.1016/S0956-053X(02)00079-X

Erses AS, Fazal MA, Onay TT, Craig WH (2005) Determination of solid waste sorption capacity for selected heavy metals in landfills. J Hazard Mater 121:223–232. https://doi.org/10.1016/j.jhazmat.2005.02.011

European Council (1999) Directive 1999/31/EC on the landfill of waste. Off J Eur Union L 182:1–19

Fan HJ, Shu HY, Yang HS, Chen WC (2006) Characteristics of landfill leachates in central Taiwan. Sci Total Environ 361:25–37. https://doi.org/10.1016/j.scitotenv.2005.09.033

Ferraz FM, Povinelli J, Pozzi E, Vieira EM, Trofino JC (2014) Co-treatment of landfill leachate and domestic wastewater using a submerged aerobic biofilter. J Environ Manag 141:9–15. https://doi.org/10.1016/j.jenvman.2014.03.022

Ferraz FM, Bruni AT, Povinelli J, Vieira EM (2016) Leachate/domestic wastewater aerobic co-treatment: a pilot-scale study using multivariate analysis. J Environ Manag 166:414–419. https://doi.org/10.1016/j.jenvman.2015.10.034

Ganigué R, López H, Balaguer MD, Colprim J (2007) Partial ammonium oxidation to nitrite of high ammonium content urban landfill leachates. Water Res 41:3317–3326. https://doi.org/10.1016/j.watres.2007.04.027

Gawande NA, Reinhart DR, Yeh GT (2010) Modeling microbiological and chemical processes in municipal solid waste bioreactor, part II: application of numerical model BIOKEMOD-3P. Waste Manag 30:211–218. https://doi.org/10.1016/j.wasman.2009.09.011

Gibbons RD, Morris JWF, Prucha CP, Caldwell MD, Staley BF (2014) Longitudinal data analysis in support of functional stability concepts for leachate management at closed municipal landfills. Waste Manag 34:1674–1682. https://doi.org/10.1016/j.wasman.2014.05.016

Grisey E, Aleya L (2016) Prolonged aerobic degradation of shredded and pre-composted municipal solid waste: report from a 21-year study of leachate quality characteristics. Environ Sci Pollut Res 23:800–815. https://doi.org/10.1007/s11356-015-5315-8
Huber WC, Dickinson RE (1988) Storm water management model; version 4. Environmental Protection Agency, United States
Hullings D (2017) The benefits of exposed geomembrane covers for intermediate applications at landfills. In: Brandon TL, Valentine RJ (eds) Geotechnical frontiers 2017. ASCE, Orlando, pp 251–258
Jianguo J, Yong Y, Shihui Y, Bin Y, Chang Z (2010) Effects of leachate accumulation on landfill stability in humid regions of China. Waste Manag 30:848–855. https://doi.org/10.1016/j.wasman.2009.12.005
Kalčíková G, Zagorc-Končan J, Zupančič M, Gotvajn AŽ (2012) Variation of landfill leachate phytotoxicity due to landfill ageing. J Chem Technol Biotechnol 87:1349–1353. https://doi.org/10.1002/jctb.3776
Kamalan H, Sabour M, Shariatmadari N (2011) A review on available landfill gas models.pdf. J Environ Sci Technol 4:79–92. https://doi.org/10.3923/jest.2011.79.92
Kamaruddin MA, Yusoff MS, Rui LM, Isa AM, Zawawi MH, Alrozi R (2017) An overview of municipal solid waste management and landfill leachate treatment: Malaysia and Asian perspectives. Environ Sci Pollut Res 24:26988–27020. https://doi.org/10.1007/s11356-017-0303-9
Kjeldsen P, Barlaz MA, Rooker AP, Baun A, Ledin A, Christensen TH (2002) Present and long-term composition of MSW landfill leachate: a review. Crit Rev Environ Sci Technol 32:297–336. https://doi.org/10.1080/10643380290813462
Koda E, Zakowicz S (1999) Physical and hydraulic properties of the MSW for water balance of the landfill, Sêco e Pin. Rotterdam, Holland
Laner D, Fellner J, Brunner PH (2011) Future landfill emissions and the effect of final cover installation—a case study. Waste Manag 31:1522–1531. https://doi.org/10.1016/j.wasman.2011.02.022
Lo IMC (1996) Characteristics and treatment of leachates from domestic landfills. Environ Int 22:433–442. https://doi.org/10.1016/0160-4120(96)00031-1
Lobo A, Tejero I (2007a) MODUELO 2: a new version of an integrated simulation model for municipal solid waste landfills. Environ Model Softw 22:59–72. https://doi.org/10.1016/j.envsoft.2005.11.003
Lobo A, Tejero I (2007b) Application of simulation models to the diagnosis of MSW landfills: an example. Waste Manag 27:691–703. https://doi.org/10.1016/j.wasman.2006.04.015
Lobo A, López A, Cobo N (2011) Modeling of biodegradation in an old unregulated European landfill. J Environ Eng 137:93–96. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000292
Lobo A, Herrero J, Montero O et al (2002a) Modelling for environmental assessment of municipal solid waste landfills (part 1: hydrology). Waste Manag Res 20:198–210. https://doi.org/10.1177/0734242X0202000211
Lobo A, Herrero J, Montero O et al (2002b) Modelling for environmental assessment of municipal solid waste landfills (part II: biodegradation). Waste Manag Res 20:514–528. https://doi.org/10.1177/0734242X0202000605
Lopez A, Pagano M, Volpe A, Di Pinto AC (2004) Fenton's pre-treatment of mature landfill leachate. Chemosphere 54:1005–1010. https://doi.org/10.1016/j.chemosphere.2003.09.015
López A, Cobo N, Tejero I, Lobo A (2008) Simulation of municipal solid waste reactors using Moduelo. Proc ICE Waste Resour Manag 161:99–104. https://doi.org/10.1680/warm.2008.161.3.99
López A, Cobo N, Cuartas M, Lobo A (2009) Estimating the future emissions of an old landfill by simulation. In: Proceedings Sardinia 2009, Twelfth International Waste Management and Landfill Symposium. CISA Publisher, S. Margherita di Pula, Cagliari
López A, Gonzalorena R, Cuartas M, Lobo A (2012) Modelación de una celda vertedero experimental con Moduelo 4.0. Rev Int Contam Ambient 28(1):89–96
Lou Z, Dong B, Chai X et al (2009) Characterization of refuse landfill leachates of three different stages in landfill stabilization process. J Environ Sci 21:1309–1314. https://doi.org/10.1016/S1001-0742(08)62400-6
McDougall J (2007) A hydro-bio-mechanical model for settlement and other behaviour in landfilled waste. Comput Geotech 34:229–246. https://doi.org/10.1016/j.compgeo.2007.02.004
Mishra H, Karmakar S (2018) A long-term comparative assessment of human health risk to leachate-contaminated groundwater from heavy metal with different liner systems. Environ Sci Pollut Res Int 25:2911–2923. https://doi.org/10.1007/s11356-017-0717-4
Morris JWF, Barlaz MA (2011) A performance-based system for the long-term management of municipal waste landfills. Waste Manag 31:649–662. https://doi.org/10.1016/j.wasman.2010.11.018
Oweis IS, Smith DA, Ellwood RB, Greene DS (1990) Hydraulic characteristics of municipal refuse. J Geotech Eng 116:539–553. https://doi.org/10.1061/(ASCE)0733-9410(1990)116:4(539)
Price GA, Barlaz MA, Hater GR (2003) Nitrogen management in bioreactor landfills. Waste Manag 23:675–688. https://doi.org/10.1016/S0956-053X(03)00104-1
Renou S, Givaudan JG, Poulain S, Dirassouyan F, Moulin P (2008) Landfill leachate treatment: review and opportunity. J Hazard Mater 150:468–493. https://doi.org/10.1016/j.jhazmat.2007.09.077
Robqeck M, Ricken T, Widmann R (2011) A finite element simulation of biological conversion processes in landfills. Waste Manag 31:663–669. https://doi.org/10.1016/j.wasman.2010.08.007
Rosqvist H, Destouni G (2000) Solute transport through preferential pathways in municipal solid waste. J Contam Hydrol 46:39–60. https://doi.org/10.1016/S0169-7722(00)00127-3
Rowe RK, Islam MZ (2009) Impact of landfill liner time-temperature history on the service life of HDPE geomembranes. Waste Manag 29:2689–2699. https://doi.org/10.1016/j.wasman.2009.05.010
Sanchez R, Tsotsis TT, Sahimi M (2010) Computer simulation of gas generation and transport in landfills. IV. Modeling of liquid-gas flow. Chem Eng Sci 65:1212–1226. https://doi.org/10.1016/j.ces.2009.09.076
Schiopu AM, Gavrilescu M (2010) Options for the treatment and management of municipal landfill leachate: common and specific issues. Clean - Soil Air Water 38:1101–1110. https://doi.org/10.1002/clen.200900184
Schroeder PR, Dozier TS, Zappi PA et al (1994) The hydrologic evaluation of landfill performance (HELP) model. Engineering documentation for version 3. Environmental Protection Agency, United States
Slack RJ, Gronow JR, Voulvoulis N (2005) Household hazardous waste in municipal landfills: contaminants in leachate. Sci Total Environ 337:119–137. https://doi.org/10.1016/j.scitotenv.2004.07.002
Stegmann R, Heyer K, Cossu R (2005) Leachate treatment. Tenth Int Waste Manag Landfill Symp
Tatsi A, Zouboulis A (2002) A field investigation of the quantity and quality of leachate from a municipal solid waste landfill in a Mediterranean climate (Thessaloniki, Greece). Adv Environ Res 6:207–219. https://doi.org/10.1016/S1093-0191(01)00052-1
Tchobanoglous G, Theisen H, Vigil SA (1993) Integrated solid waste management: engineering principles and management issues. McGraw-Hill, London
Wang Y, Pelkonen M, Kaila J (2012) Optimization of landfill leachate management in the aftercare period. Waste Manag Res 30:789–799. https://doi.org/10.1177/0734242X12440483
White JK, Nayagum D, Beaven RP (2014) A multi-component two-phase flow algorithm for use in landfill processes modelling. Waste Manag 34:1644–1656. https://doi.org/10.1016/j.wasman.2014.05.005

Wu JJ, Wu CC, Ma HW, Chang CC (2004) Treatment of landfill leachate by ozone-based advanced oxidation processes. Chemosphere 54: 997–1003. https://doi.org/10.1016/j.chemosphere.2003.10.006

Yuan Q, Jia H, Poveda M (2016) Study on the effect of landfill leachate on nutrient removal from municipal wastewater. J Environ Sci (China) 43:153–158. https://doi.org/10.1016/j.jes.2015.10.023

Zhao R, Gupta A, Novak JT, Goldsmith CD (2017) Evolution of nitrogen species in landfill leachates under various stabilization states. Waste Manag 69:225–231. https://doi.org/10.1016/j.wasman.2017.07.041

Ziyang L, Youcai Z, Tao Y, Yu S, Huili C, Nanwen Z, Renhua H (2009) Natural attenuation and characterization of contaminants composition in landfill leachate under different disposing ages. Sci Total Environ 407:3385–3391. https://doi.org/10.1016/j.scitotenv.2009.01.028