Environmental Engineering and Management Journal
May 2018, Vol.17, No. 5, 1189-1198
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

COST-EFFECTIVENESS ANALYSIS OF DIFFERENT LANDFILL COVERS IN SEMIARID ZONES

Javier Senent-Aparicio[1], Francisco Pellicer-Martínez[1], Ángel Perni[2]*, José M. Martínez-Paz[2]

[1]*Escuela Universitaria Politécnica, Universidad Católica San Antonio de Murcia, CP. 30107, Murcia, Spain*
[2]*Departamento de Economía Aplicada, Facultad de Economía y Empresa, Universidad de Murcia, CP. 30100, Murcia, Spain*

Abstract

In order to reduce the production of pollutants, it is most important that landfills are adapted to the climatic conditions of the area where they are located. In this sense, there are very few studies focused on how to reduce leachates from landfills in semiarid regions, which are especially sensitive to the impacts that this type of activity potentially has on water resources. The aim of this study is to identify the best type of landfill cover that reduces leachate production in semiarid regions by means of a Cost-Effectiveness Analysis (CEA). Three types of covers are evaluated: conventional multilayer, monolithic and mixed monolithic. The evaluation of the effectiveness of each alternative has been carried out with the HELP model (Hydrologic Evaluation of Landfill Performance), which allows for the estimation of the reduction of leachates. Results show that mixed monolithic cover is the most cost-effective alternative. In contrast, monolithic cover is an even worse alternative than the status quo, so its implementation may be not recommended in semiarid regions.

Key words: Cost-Effectiveness Analysis, HELP model, landfill, leachate, pollution

Received: July, 2013; Revised final: August, 2014; Accepted: August, 2014; Published in final edited form: May, 2018

1. Introduction

The management of municipal solid waste (MSW) is one of the main environmental challenges worldwide (Buenrostro et al., 2012; Vergara and Tchobanoglous, 2012). Proper management should aim at reducing MSW, either by preventing its generation or through recycling. However, in the case of the European Union (EU), approximately 50% of the waste generated still ends up being deposited in landfills. Although rates for municipal waste landfill steadily decreased from 62% to 40% in the period 1994-2008 (EEA, 2010), they still put significant pressure on the environment. The main problems caused by landfills are: the seized area, soil and water contamination by leachates and the emission of greenhouse gases. Therefore, landfills must have systems that minimize these effects on the environment, both in the operational phase and in the final capping, once the activity has ceased. These systems must be effective to reduce pollution, and their design should suit the climatic conditions of the area where they are located (Baziene et al., 2013; Laner et al., 2012). In addition, new approaches for landfill management highlight the opportunity of resource recovery (Dino et al., 2017; Jones et al., 2013) and the need to take into account social perspectives (Van Passel et al., 2013) so as to reach a higher level of environmental sustainability.

Landfill cover systems for reducing landfill pollution have been studied mainly from a technical viewpoint. In general, the literature deals with aspects such as methane emission reduction (Park et al., 2010), landfill water balance for specific covers (Nyhan, 2005), comparison of open and closed landfill conditions (Visvanathan et al., 2011), and analysis of

---

* Author to whom all correspondence should be addressed: e-mail: angel.perni@um.es; Phone: 0034 868 88 7605

seasonal patterns of leachate production for long-term design of landfills (Kim and Lee, 2009; Henken-Mellies and Schweizer, 2011). However, studies integrating technical and economic arguments to select cover systems are still lacking. In particular, there are very few studies that analyze the feasibility of cover systems based on cost-effectiveness analysis (CEA), even though it has already been used to analyse the efficiency of measures related to different aspects of solid waste management with the aim of selecting the best alternative that meets a specific objective (Chang et al., 2012; Clarke, 2000, Harbottle et al., 2007; Li et al., 2016; Lombrano, 2009; Wang and Wang, 2006; Weng and Fujiwara, 2011).

In this paper, we evaluate three types of landfill cover systems (conventional multilayer, monolithic and monolithic mixed) in a semiarid area with a Mediterranean climate by means of CEA. Indeed, its application is even more crucial to evaluate landfill cover systems in semiarid regions, which are especially sensitive to the impacts of leachates on scarce water resources (Tatsi and Zouboulis, 2002) that may also originate other socio-economic impacts.

2. Case study

The landfill studied is located in Fuente-Alamo (Murcia, SE Spain), in the *Campo de Cartagena* basin, which covers an area of about 1,200 km^2 (Fig. 1). The area's climate is semiarid and has an average annual rainfall of 300 mm, a mean annual temperature of 18ºC and the potential evapotranspiration is over 1,000 mm / year (Pellicer-Martinez and Martinez-Paz, 2018). Despite the low rainfall rates, precipitations can be very intense, mainly in late summer and early autumn, and may cause floods (Conesa-Garcia et al., 2010). The *Campo de Cartagena* basin flows into the Mar Menor, one of the largest lagoons in the Mediterranean region. This coastal lagoon is included in the Ramsar list of wetlands (Perni and Martinez-Paz, 2017). It is also located over an important aquifer whose water is used to help maintain the agriculture in the area (Martinez-Paz et al., 2015). Therefore, proper management of the landfill is crucial to avoid damaging the status of other water bodies in the basin.

The surface area of the Fuente Alamo is 259,000 m^2 including the disposal area and ancillary facilities. The disposal area occupies 130,752 m^2 of the total area and is divided into two cells (labelled A and B). The surface area, gross volume and operational life of each cell are shown in Table 1.

Table 1. Area, volume and operational life of the Fuente Alamo landfill

	Cell A (being exploited)	***Cell B (soon to be exploited)***
Installation surface area (m^2)	62,116	68,636
Gross volume (m^3)	913,211	836,081
Operational life (years)	10	10

The facility came into operation in 2003 with Cell A and by 2013 this cell had reached its full capacity and is scheduled to be covered shortly, after which Cell B will come into operation. For this reason, the case study for this paper is Cell A. The waste from the cell is stored in compacted layers alternating residues and clays, 0.5 meter and 0.15 meter thick respectively.

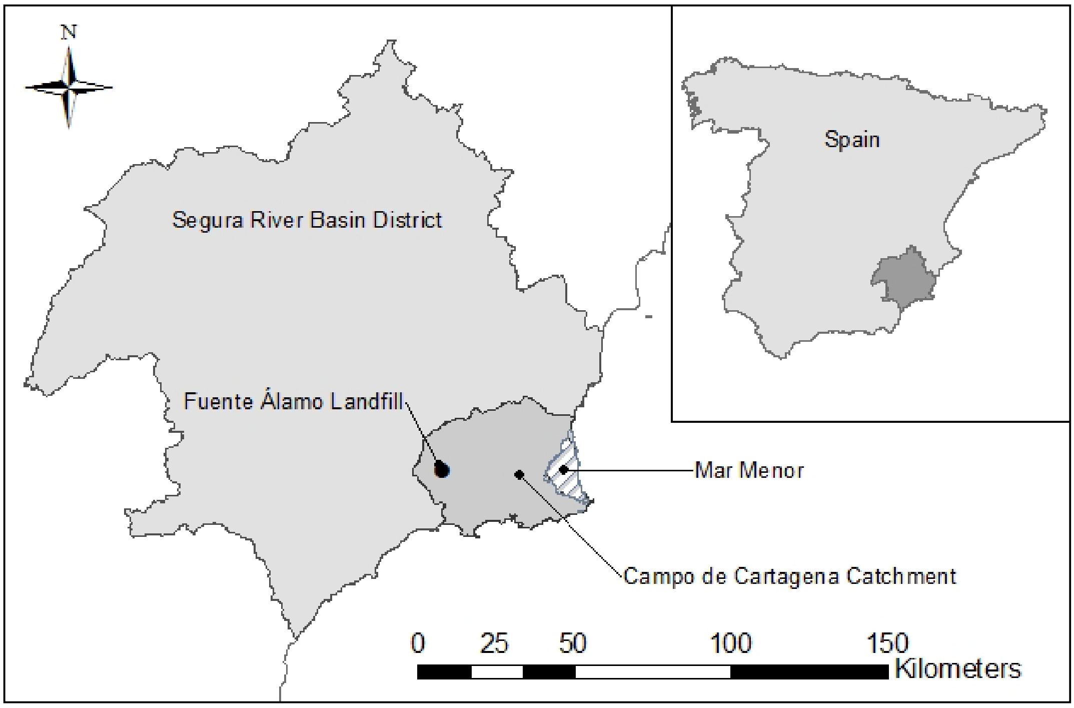


Fig. 1. Location of the Fuente Alamo landfill

This cell is hydrologically isolated by a perimeter ditch that prevents the entry of surface runoff water into the cell, leading that runoff water to a 700 m^3 pool. In addition, a bentonite layer at the bottom of the cell prevents leachate leaking into the aquifer. In the bottom of the cell there is a drainage network which captures and disposes of the generated leachates into a 400 m^3 pond where it is stored until further processing.

The main source of landfill waste is MSW from the nearby towns. Waste collection is carried out selectively; therefore, the majority of recyclable materials do not end up in the landfill. The main characteristics of these residues are shown later in Table 3.

3. Material and methods

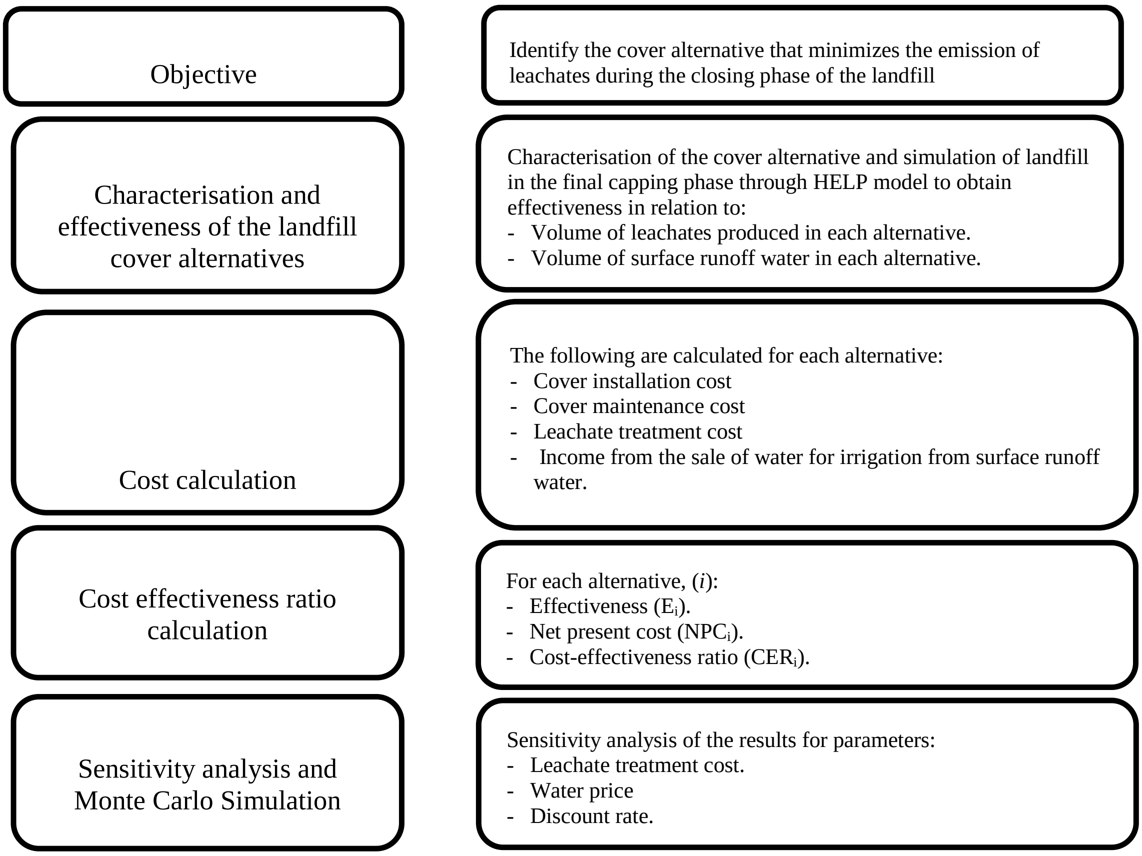
3.1. Cost-Effectiveness Analysis

The CEA is a decision-making assistance tool. It identifies the economically most efficient way to fulfil an objective, by comparing different actions with regards to a common aim (Perni and Martinez-Paz, 2013). This method is applied to compare management alternatives that can quantify the costs of implementation, but it is difficult, sometimes even impossible, to quantify in economic terms all the advantages. This technique is widely used in the assessment of social and public policy, and is being increasingly used in the environmental field (Finnveden et al., 2007). The CEA consists in (Brouwer and De Blois, 2008): (i) establishing an objective, (ii) identifying alternatives, (iii) estimating effectiveness and costs of the alternatives, (iv) ranking the alternatives according to a cost ratio-effectiveness, (v) selecting the combination of measures that are more cost-effective, and (vi) performing a sensitivity analysis of the results. Fig. 2 summarizes the methodology used for the evaluation of alternative landfill covers. The goal is to identify the landfill cover alternative that minimizes the emission of leachate during the closing phase of the landfill. The different stages are explained in the following sections.

3.2. Characterization of the landfill cover alternatives

This paper evaluates three alternatives for the covering of the Fuente Alamo landfill: conventional multilayer cover (CC), monolithic cover (MC) and mixed monolithic cover (MMC). Once the last layer of solid waste for each landfill cover alternative is prepared, a regularizing layer is placed on the waste in order to create a uniform surface area that serves as a support to the other cover layers.

The position and type of cover layers for the CC are regulated as per the legislation for landfill management established by the Spanish Ministry of Agriculture, Food and Environment (BOE, 2001).



Objective

Identify the cover alternative that minimizes the emission of leachates during the closing phase of the landfill

Characterisation and effectiveness of the landfill cover alternatives

Characterisation of the cover alternative and simulation of landfill in the final capping phase through HELP model to obtain effectiveness in relation to:
- Volume of leachates produced in each alternative.
- Volume of surface runoff water in each alternative.

Cost calculation

The following are calculated for each alternative:
- Cover installation cost
- Cover maintenance cost
- Leachate treatment cost
- Income from the sale of water for irrigation from surface runoff water.

Cost effectiveness ratio calculation

For each alternative, (*i*):
- Effectiveness (E_i).
- Net present cost (NPC_i).
- Cost-effectiveness ratio (CER_i).

Sensitivity analysis and Monte Carlo Simulation

Sensitivity analysis of the results for parameters:
- Leachate treatment cost.
- Water price
- Discount rate.

Fig. 2. General methodological framework

Table 2 shows the composition and characteristics of the layers used for each cover. A layer of polyethylene insulating sheet is placed over the regularization layer, which reduces the entry of rainwater, thus decreasing the production of leachates. The cover structure is then covered with gravel drainage and, finally, a sandy clay coating is placed on top to facilitate the growth of vegetation on the landfill. The alternative MC is based on the Evapotranspiration Landfill Cover System (ET Cover) (Hauser et al., 2001) which has been applied in semiarid regions with satisfactory results (Albright et al., 2004). This type of cover consists of a single layer of clay silts on the regularizing layer. This system uses the hydrological characteristics of the soil to store water from precipitation in the form of soil moisture and return it to the atmosphere through evapotranspiration.

The structure and operation of the MMC is similar to that of MC. In this case, a layer of clayey silts similar to that of the MC is placed on the regularizing layer, but the top 20 cm of the layer is replaced with a combination of clayey silt (60%) and compost (40%) (Elshorbagy and Mohamed, 2000).

3.3. Estimation of effectiveness using HELP model.

To evaluate the effectiveness of each alternative, this paper applies the HELP model, a water balance model designed for and applied specifically to the management of landfills (Schroeder et al., 1994). In this paper we have studied the case of the Fuente Alamo landfill, located in the semiarid *Campo de Cartagena* basin (SE Spain).

The behaviour of the different types of landfill cover varies with regard to leachate production and this then determines their effectiveness. The effectiveness of each type of cover (E_i) to reduce leachates is given by the following expression (Eq. 1).

$$E_i = 1 - \frac{VLT_{SQ}}{VLT_i} \tag{1}$$

where: VLT_{SQ} and VLT_i are, respectively, the total volume of leachates produced in the uncovered alternative (*status quo*, SQ) and the covered alternative *i* (CC, MC, MMC) throughout the duration of the analysis.

A positive value of the ratio indicates that alternative *i* produces less leachates and therefore is more efficient than alternative SQ. On the contrary, a negative value indicates a less effective alternative *i* regarding alternative SQ. The zero value indicates that both alternatives are equally effective.

VLT_{SQ} and VLT_i are obtained by simulating the landfill cover phase for each alternative using the HELP model (Schroeder et al., 1994). This model simulates the water balance of a MSW landfill in order to estimate the volume of leachates produced over a period of time. The inputs to the model are the geometry of the landfill basin, the characteristics of the construction materials, the characteristics of the waste stored, the landfill management, the weather of the location and the type of cover. Four water balance simulations have been performed, one for each cover alternative and the SQ alternative.

The design variables and structure of the landfill and the waste characteristics are constant for the model, while climatic variables are time series. The latter have been estimated from the synthetic series generator HELP model for the period 2012-2024, using as reference measurements for the period 1999-2011 from the Weather Station CA91 of the SIAM Network (Agricultural Information System of Murcia, Spain), located 8 km from the landfill.

3.4. Costs of landfill cover alternatives

The costs of each alternative are divided into the following categories: initial investment costs, operational and maintenance costs, and leachate management costs. In addition to the characteristics of each type of cover, the HELP model incorporates the variables shown in Table 3.

The initial investment costs refer to those required to prepare the waste prior to the landfill cover, as well as installation costs of the cover system. These costs have been estimated from information provided by the company who exploits the facility at present and have been updated to 2011.

Table 2. Layers of landfill covers

Alternative	*Layers**	*Material*	*Thickness (m)*	*K (cm/s)*
CC	Top coat	Loamy sand	1.00	$5.2\cdot10^{-4}$
	Filtering	Fine sands	0.30	10^{-3}
	Mineral drainage	Coarse sands	0.30	10^{-2}
	Impermeable barrier	High density polyethylene sheets	0.02	$2\cdot10^{-13}$
	Regularizing layer	Moderately compact sandy loam	0.50	$1.9\cdot10^{-6}$
MC	Cover	Clayey silts	1.00	10^{-6}
	Regularizing layer	Moderately compact sandy loam	0.50	$1.9\cdot10^{-6}$
MMC	Cover	Clayey silts (60%) + Compost (40%)	0.20	$2\cdot10^{-8}$
		Clayey silts	0.80	10^{-6}
	Regularizing layer	Moderately compact sandy loam	0.50	$1.9\cdot10^{-6}$

*CC: Conventional multilayer cover, MC: Monolithic cover, MMC: Mixed Monolithic cover; *Layers sorted according to their position in the cover system, from more to less superficial*

The cost of waste treatment (5,100 €) is common to all the alternatives and the alternative cover SQ (Table 4). The maintenance and operational costs of the cover system are divided into five items. First, maintenance costs equal to the 0.5% of the initial investment (Ortiz and Rivero, 2006). Second and third, the maintenance costs of drainage and leachate collection systems. These are the same for the four cases analyzed and have been obtained from the information in the technical project for the execution of landfills. Fourth, the starting material replacement costs. Finally, the costs of the Environmental Monitoring Plan have been included; these were obtained from the environmental impact study for the landfill.

The cost of the leachate treatment depends on the total volume produced which is different for each landfill cover alternative. This volume is estimated by the HELP model, and is given by the variable VLT_i. After consulting, among others, the works of Rautenbach et al. (1996), Lema et al. (1998), Yalili et al. (2007), Renou et al. (2008), Salem et al. (2008) and Ruscadella (2012), in which various considerations are made on the costs of the different leachate treatments, a range between 0.6 €/m^3 and 18.3 €/m^3 at 2011 prices has been obtained. Initially a unit cost of 2 €/m^3 has been estimated, corresponding to a standard rapid dehydration treatment and handling of sludge, though this range of variation is used later in a sensitivity analysis of the results.

The surface runoff water can be used for irrigation, one of the main economic activities in the region. For this reason, the income obtained from the sale of water has also been included in the analysis. The water price in the area varies from 0 €/m^3, if the water has no further use, to a maximum value of 0.3 €/m^3, which represents the opportunity cost of an alternative source of water for irrigation in the area (Colino and Martinez-Paz, 2007). Runoff water from the landfill cannot be used directly in farming and requires a pretreatment. For this reason, based on the analysis, an initial conservative value of 0.1 €/m^3 has been established. The total annual income is obtained by multiplying this price by the total amount of runoff water captured by drainage and landfill buildup. This volume is provided by the HELP model.

Table 3. Factors and input variables entered into HELP model

	Parameter		***Value***	***Data source***
Design data	Area (ha)		62,000	Management firm
	Cover slope (%)		3%	
	Drainage distance in leachate collection layer (m)		200	
	Slope of drainage layer in leachate collection system (%)		1.5	
	Leaf area index		1.5	
	Evaporative zone depth (cm)		53	
Waste characteristics	Porosity (vol/vol)		0.671	Management firm Schroeder et al. (1994)
	Field capacity (vol/vol)		0.292	
	Wilting point (vol/vol)		0.077	
	Hydraulic conductivity (vol/vol)		0.001	
	Initial moisture content (vol/vol)		0.222	
Meteorological Data	Average annual precipitation (mm)		286	Weather station of SIAM Network
	Average annual temperature (ºC)		17.4	
	Average annual solar radiation (kwh/m^2 day)		4.69	
	Average annual wind speed (km/h)		4.75	
	Average quarterly relative humidity (%)	Winter	70	
		Spring	61	
		Summer	64	
		Autumn	71	

Table 4. Costs and income of the landfill cover alternatives (€$_{2011}$)

Concept		***SQ***	***CC***	***MC***	***MMC***
Initial investment (Conditioning of waste and cover; €)		5,100	2,552,742	1,025,000	979,368
Maintenance and operational costs	Cover maintenance (0.5% of initial investment; €/year)	26	12,764	5,125	4,897
	Maintenance of drainage system (€/year)	1,200			
	Maintenance of leachate system (€/year)	2,350			
	Material replacement (€/year)	1,550			
	Environmental monitoring plan (€/year)	3,823			
Cost of leachate treatment (€/m^3/year)		2.00			
Runoff water price (€/m^3/year)		0.10			

SQ: Status quo; CC: Conventional multilayer cover, MC: Monolithic cover, MMC: Mixed Monolithic cover

Whether the costs of all alternatives are comparable, the Net Present Cost (NPC) has been estimated. The updated NPC of each alternative *i* is estimated as follows (Eq. 2):

$$NPC_i = I_0 + \sum_{j=1}^{t} \frac{C_j}{\left(1+d\right)^j} \qquad (2)$$

where: I_0 is the initial investment, C_j is the result of adding together the costs of maintenance, running of the landfill and the leachate treatment costs and of subtracting the income from to the sale of water in year *j*; *d* is the discount rate and *t* is the useful life of the measure, which defines the time horizon of the evaluation.

The discount rate used is 3% (Almansa and Martinez-Paz, 2011a), and the time horizon corresponds to the period from 2011 to 2024. The costs related to the initial investment are assigned to the first year, while the other costs and income take place throughout the period.

Once NPC_i is obtained, the relative cost of each alternative *i* is estimated compared to the inaction alternative (SQ) (Eq. 3):

$$NPCr_i = \frac{NPC_i}{NPC_{SQ}} - 1 \qquad (3)$$

where: NPC_{SQ} and NPC_i are the net present costs for the entire period of analysis for SQ alternative and cover alternative *i*, respectively. This represents the increase of the relative cost that the alternative *i* has over that of SQ, the ratio has been constructed so that the positive values indicate a higher cost of the evaluated alternative over that of SQ. The value zero indicates equal costs of the alternative and negative values indicate a lower cost of the alternative differential with respect to the base situation.

3.5. Cost-effectiveness ratios

The cost-effectiveness ratios (CER) show which alternative is able to reduce leachate production more efficiently. In this study the CER is determined by the following expression (Eq. 4):

$$CER_i = \frac{E_i}{NPCr_i} \qquad (4)$$

where: NPC_i is the relative cost of the alternative to SQ and E_i refers to the efficiency required to measure *i*. An alternative "*a*" would be more cost-effective than alternative "*b*" given that $CER_a > CER_b$, i.e. the most appropriate alternative is the one with a higher CER_i value. Whereas a conventional cost-effectiveness ratio shows the unit cost to reduce by one unit the amount of pollution produced, the ratio proposed in this paper is capable of isolating the effects and costs attributable to each of the alternatives, given that both components are expressed in relative terms with regards to the inaction alternative (SQ). Alternatively, some authors propose incremental cost-effectiveness ratios to rank alternatives in a progressive way, i.e., by determining the ratio of the change in cost to the change in effect (Compernolle et al., 2012). However, in the case of landfill covers, alternatives must be compared in terms of their capacity to treat the highest possible amount of leachates generated during the last phase of the activity.

4. Results and discussion

4.1. Results of the simulation of hydrological balance and estimate costs and effectiveness

In general, the different sets of volumes of leachates obtained have a low correlation and even have different leachates generation patterns throughout the annual series. Only the MMC and MC alternatives show a strong correlation of 0.90, which is explained by the similarity between the structures of the landfill covers. This shows the influence that each type of cover has on the hydrological behaviour of the landfill as a whole. The opposite occurs in the series of volumes of runoff water, which show a strong correlation (> 0.80, in all cases). This is due to the fact that the formation of runoff water depends solely on the characteristics of the upper layer, which is similar in all the alternatives.

The simulation of the hydrological balance of the landfill also allows us to reproduce climate patterns for semiarid Mediterranean areas. For example, the model predicts high variability in the production of leachates. For instance, 2014 and 2015 represent wet years, whereas 2017 and 2018 are dry years. These results match those obtained by Tatsi and Zouboulis (2002), who concluded that in the Mediterranean region there may be seasonal fluctuations in the quality and quantity of landfill leachates produced.

The most effective alternatives are the MMC and CC with leachate reduction rates of 98% and 97% compared to the alternative SQ, respectively. By contrast, the landfill cover MC produces 202% more leachates than the alternative of reference (SQ), which indicates that the installation of this type of cover in semiarid regions is counterproductive.

4.2. Ranking of alternatives

Furthermore, the cost-effectiveness ratio corresponding to the conventional cover shows a clear positive effect, but it is considerably inferior when compared to that obtained by applying a mixed monolithic cover.

Table 5. Volumes (m^3/year) per year of leachates and runoff water for landfill cover alternatives

	Leachates				***Runoff water***			
Year	***SQ***	***CC***	***MC***	***MMC***	***SQ***	***CC***	***MC***	***MMC***
2012	76	0	18	72	0	7,436	2,396	10,021
2013	32	3	367	31	0	8,959	3,817	11,869
2014	3,113	17	1,369	1	0	17,663	10,572	22,642
2015	654	28	2,072	1	0	7,680	5,753	11,989
2016	75	15	1,864	1	0	7,435	5,332	10,670
2017	33	16	1,963	1	0	8,500	3,534	13,171
2018	1	18	1,517	1	0	4,480	4,281	7,008
2019	743	17	1,681	1	0	12,329	9,159	15,434
2020	291	13	1,516	1	0	10,823	4,946	15,474
2021	56	19	1,856	1	0	14,365	10,.577	17,994
2022	31	16	1,744	1	0	13,491	9,278	16,367
2023	1,182	18	1,522	1	0	12,810	9,140	16,564
2024	71	15	1,721	1	0	7,499	4,326	10,942

SQ: Status quo; CC: Conventional multilayer cover; MC: Monolithic cover; MMC: Mixed Monolithic cover

The monolithic cover (MC) alternative should be rejected from the selectable alternatives because its cost-effectiveness ratio is negative. Table 5 shows the results of the simulation of each cover alternative by means of the HELP model. Table 6 shows the total volume of leachates generated by the landfill according to the type of cover used (VLT_{SQ} and VLT_i) along the time horizon of the evaluation. With these results, we have determined the relative effectiveness (E_i) of each alternative. Finally, from the results of modelling and under the assumptions indicated in Section 3.4 for estimating costs, we have obtained the absolute and relative NPC of each cover alternative (Table 7). Table 8 shows the cost-effectiveness ratios of the three landfill cover alternatives. The most cost-effective alternative is MMS.

Table 6. Volume of leachates and effectiveness ratios of each alternative

	SQ	***CC***	***MC***	***MMC***
Total leachate (m^3)	6,358	196	19,210	115
Effectiveness (E_i)	0	31.43	-0.67	54.52

SQ: Status quo; CC: Conventional multilayer cover; MC: Monolithic cover, MMC: Mixed Monolithic cover

Table 7. Absolute and relative Net Present Cost of the landfill cover alternatives

Alternative	***NPC (€$_{2011}$)***	***NPCr***
Status Quo (SQ)	111,019	0.00
Conventional multilayer cover (CC)	2,777,019	24.01
Monolithic cover (MC)	1,194,182	9.76
Mixed monolithic cover (MMC)	1,111,899	9.02

Table 8. Cost-effectiveness ratios of landfill cover alternatives

Alternative	***CER***
Conventional multilayer cover (CC)	1.309
Monolithic cover (MC)	-0.069
Mixed monolithic cover (MMC)	6.047

4.3. Sensitivity Analysis

The most cost-effective solution is strongly influenced by the values of the parameters and variables that are part of the initial assumptions of the study: discount rate (*d*), cost of leachate treatment (*ctl*), and the value of water produced (*va*). In order to analyze how robust this solution is, a sensitivity analysis is performed. Firstly, to identify the impact of each parameter, a univariate analysis is undertaken. Next, to evaluate the uncertainty of the results, a Monte Carlo simulation is conducted varying the three parameters individually.

The ranges of variation for both analyses are:

- Discount rate (*d*): following the recommendations of Almansa and Martinez-Paz (2011b) and EC (2003) this parameter has a range of variation between 2% to 10%.
- Cost of treatment of leachates (*ctl*): as stated, this cost depends considerably on the type of treatment applied, and a range of variability between 0.6 €/m^3 to 18 €/m^3 has been established.
- Value of water produced (*va*): from the considerations in the case study, we have used a variation range from 0 to 0.30 €/m^3.

Results are shown in Fig. 3a, 3b and 3c for *d*, *ctl* and *va*, respectively. It should be stressed that the *CER* parameter is not very sensitive to the value of water (*va*) for the different alternatives, which indicates that this factor is not decisive in the economic analysis of these facilities located in semiarid areas. The cost-effectiveness ratio of the alternative MMC is more sensitive to an increase in the costs than the other two alternatives. It is due to the fact that this type of cover is the one reducing the volume of leachates to a greater degree and, hence, has a higher impact on the final costs. Finally, as the discount rate (*d*) affects both the annual costs of each alternative and the reference, the *CER* value is more sensitive in the alternatives whose relation between annual costs and initial investment differs more than the reference alternative (SQ).

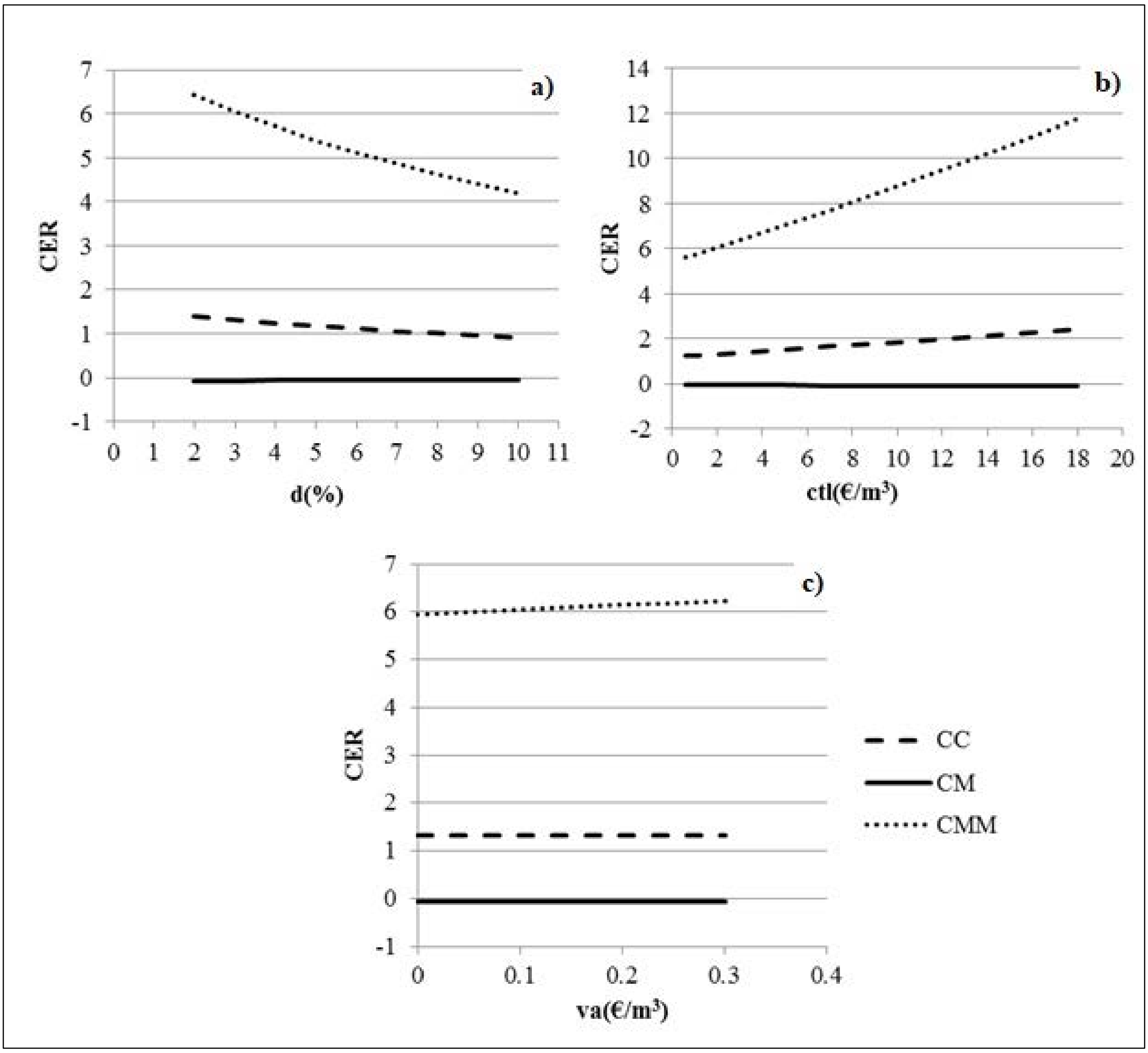


Fig. 3. Sensitivity analysis of Cost-Effectiveness Ratios (CER)

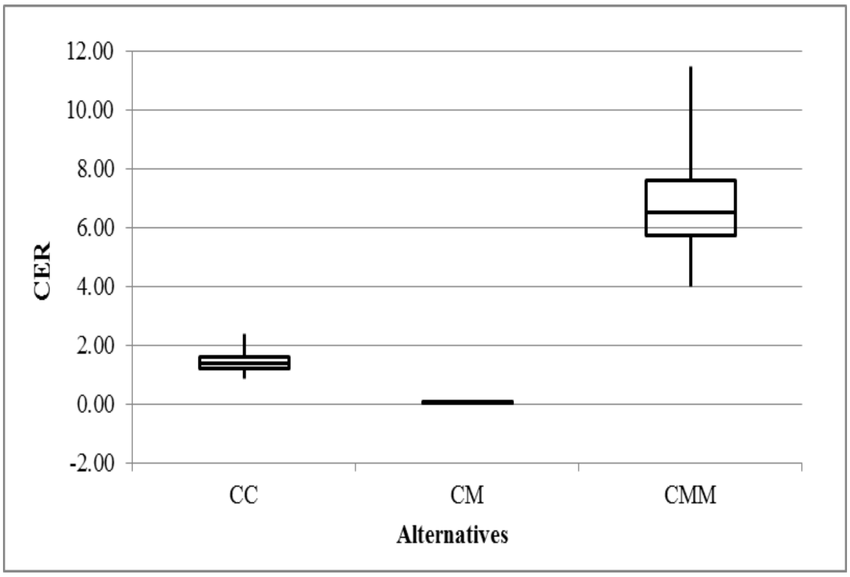


Fig. 4. Monte Carlo simulation results

This first analysis indicates that the ranking of alternatives does not change even when varying the three parameters. In this case, the most sensitive alternatives are MMC and CC.

The Monte Carlo simulation is conducted following the recommendations of Vose (2000). It is assumed that the three parameters have a triangular probability distribution since their real distribution is unknown. The ranges of variation have been presented previously and the most probable value of the distributions are: 5% for the discount rate (*d*), 2 €/m^3 for the cost of leachate treatment (*ctl*), and 0.15 €/m^3 for the value of water (*va*). 10,000 iterations are performed and the results, presented as a box-whisker plot that shows all the variability (Fig. 4), confirm that CMM landfill cover is always the most cost-effective even though this alternative has the greatest variability. The firm results of this analysis allow us to conclude that this analysis provides robustness to the results, corroborating that the CMM landfill cover is the most cost-effective alternative, regardless of cost and income issues.

5. Conclusions

This study has provided technical-economic arguments for the selection of cover systems for landfills located in semiarid areas based on both hydrological modelling and full-cost accounting. Three cover systems have been analyzed to test their ability to reduce leachates in semiarid climates.

The results show that mixed monolithic covers are the most cost-effective, followed by conventional multilayer systems. However, monolithic covers should be rejected as they may generate even more leachates than the status quo, so it is not advisable to implement this cover in semiarid areas. The sensitivity analysis of the results confirms the ranking presented herein.

Acknowledgements
Angel Perni's work has been financed thanks to a PhD scholarship from Fundación Séneca (Spain).

References

Albright W.H., Benson C.H., Gee G.W., Roesler A.C., Abichou T., Apiwantragoon P., Lyles B.F., Rock S.A., (2004), Field water balance of landfill final covers, *Journal of Environmental Quality*, **33**, 2317-2332.

Almansa C., Martinez-Paz J.M., (2011a), What weight should be assigned to future environmental impacts? A probabilistic cost benefit analysis using recent advances on discounting, *Science of the Total Environment*, **409**, 1305-1314.

Almansa C., Martinez-Paz J.M., (2011b), Intergenerational equity and dual discounting, *Environment and Development Economics*, **16**, 685-707.

Baziene K., Vasarevicius S., Baltrenas P., Baltrenaite E., (2013), Influence of total precipitation and air temperature on the composition of municipal landfill leachate, *Environmental Engineering and Management Journal*, **12**, 175-182.

BOE, (2001), Royal Decree 1481/2001, of 27 December, regulating waste disposal by landfill, (in Spanish), *Ministry of Agriculture, Food and Environment. Gazette*, **25**, 3507-3521.

Brouwer R., De Blois C., (2008), Integrated modelling of risk and uncertainty underlying the cost and effectiveness of water quality measures, *Environmental Modelling and Software*, **23**, 922-937.

Buenrostro O., Márquez L., Ojeda S., (2012), Environmental Perception of solid waste management in the municipalities of Pátzcuaro region, *Environmental Engineering and Management Journal*, **13**, 3097-3103.

Chang N.B., Qi C., Islam K., Hossain F., (2012), Comparisons between global warming potential and cost-benefit criteria for optimal planning of a municipal solid waste management system, *Journal of Cleaner Production*, **20**, 1-13.

Clarke W.P., (2000), Cost-benefit analysis of introducing technology to rapidly degrade municipal solid waste, *Waste Management and Research*, **18**, 510-524.

Colino J., Martinez-Paz J.M., (2007), Productividad, disposición al pago y eficiencia técnica en el uso del agua: la horticultura intensiva de la Región de Murcia, (in Spanish), *Economía Agraria y Recursos Naturales*, **14,** 109-125.

Compernolle T., Van Passel S., Lebbe L., Weyens N., Vangronsveld J., Thewys T., (2012), Groundwater Remediation and the cost effectiveness of phytoremediation, *International Journal of Phytoremediation*, **14**, 861-877.

Conesa-Garcia C., Caselles-Miralles V., Sanchez Tomas J.M., Garcia-Lorenzo R., (2010), Hydraulic geometry, gis and remote sensing, techniques against rainfall-runoff models for estimating flood magnitude in ephemeral fluvial systems, *Remote Sensing*, **2**, 2607-2628.

Dino G.A., Rossetti P., Biglia G., Sapino M.L., Di Mauro F., Sarkka H., Coulon F., Gomes D., Parejo-Bravo L., Aranda P.Z., Lopez A.L., Lopez J., Garamvolgyi E., Stojanovic S., Pizza A., de la Feld M., (2017), Smart ground project: a new approach to data accessibility and collection for raw materials and secondary raw materials in Europe, *Environmental Engineering and Management Journal*, **16**, 1673-1684.

EC, (2003), European Commission. Guide to cost-benefit analysis of investment projects: Structural Funds-ERDF, Cohesion Fund and ISPA, prepared for the Evaluation Unit, Brussels: DG Regional Policy.

Elshorbagy W.A., Mohamed A.M.O., (2000), Evaluation of using municipal solid waste compost in landfill closure caps in arid areas, *Waste Management*, **20**, 499-507.

Finnveden G., Bjoerklund A., Moberg A., Ekvall T., (2007), Environmental and economic assessment methods for waste management decision-support: possibilities and limitations, *Waste Management and Research*, **25**, 263-269.

Harbottle M.J., Al-Tabbaa A., Evans C.W., (2007), A comparison of the technical sustainability of in situ stabilisation/solidification with disposal to landfill, *Journal of Hazardous Materials*, **141**, 430-440.

Hauser V.L., Weand B.L., Gill M.D., (2001), Natural covers for landfills and buried waste, *Journal of Environmental Engineering-ASCE*, **127**, 768-775.

Henken-Mellies W.U., Schweizer A., (2011), Long-term performance of landfill covers - results of lysimeter test fields in Bavaria (Germany), *Waste Management and Research*, **29**, 59-68.

Jones P.T., Geysen D., Tielemans Y., Van Passel S., Pontikes Y., Blanpain B., Quaghebeur M., Hoekstra N., (2013), Enhanced landfill mining in view of multiple resource recovery: a critical review, *Journal of Cleaner Production*, **55**, 45-55.

Kim Y.D., Lee D.G., (2009), Comparative study on leachate in closed landfill sites: focusing on seasonal variations, *Journal of Material Cycles and Waste Management*, **11**, 174-182.

Laner D., Crest M., Scharff H., Morris J. W. F., Barlaz, M. A., (2012), A review of approaches for the long-term management of municipal solid waste landfills, *Waste Management*, **32**, 498-512.

Lema J.M., Mendez R., Blazquez R., (1998), Characteristics of landfill leachates and alternatives for their treatment: A review, *Water, Air and Soil Pollution*, **40**, 223-250.

Li Y.P., Sun Y., Huang G.H., Zhao F., (2016), An interval-parameter queuing model for planning municipal solid waste management system with cost-effective objective, *Environmental Engineering and Management Journal,* **15**, 1673-1687.

Lombrano A., (2009), Cost efficiency in the management of solid urban waste, *Resources Conservation and Recycling*, **53**, 601-611.

Martinez-Paz J.M., Pellicer-Martínez F., Ramón J., Lamonaca L., (2015), Valoración socioeconómica de la extracción de gas mediante fracturación hidráulica en la Región de Murcia, (in Spanish), *Papeles de Geografía*, **61**, 122-136.

Nyhan J.W., (2005), A seven-year water balance study of an evapotranspiration landfill cover varying in slope for semiarid regions, *Vadose Zone Journal*, **4**, 466-480.

Ortiz A., Rivero G., (2006), *Cost Structure: Concepts and Methodology*, (in Spanish), Pactworld, USA.

Park S., Brown K.W., Thomas J.C., Lee I.C., Sung K., (2010), Comparison study of methane emissions from landfills with different landfill covers, *Environmental Earth Sciences*, **60**, 933-941.

Pellicer-Martinez F., Martinez-Paz J.M., (2018), Probabilistic evaluation of the water footprint of a river basin: Accounting method and case study in the Segura River Basin, Spain, *Science of the Total Environment*, **627**, 28-38.

Perni A., Martinez-Paz J.M., (2013), A participatory approach for selecting cost-effective measures in the WFD context: The Mar Menor (SE Spain), *Science of the Total Environment*, **458/460**, 303-311.

Perni A., Martinez-Paz J.M., (2017), Measuring conflicts in the management of anthropized ecosystems: Evidence from a choice experiment in a human-created Mediterranean wetland, *Journal of Environmental Management*, **203**, 40-50.

Rautenbach R., Vossenkaul K., Linn T., Katz T., (1996), Wastewater treatment by membrane process. New development in ultrafiltration, nanofiltration and reverse osmosis, *Desalination*, **108**, 247-253.

Renou S., Givaudan J.G., Poulain S., Dirassouyan F., Moulin P., (2008), Landfill leachate treatment: Review and opportunity, *Journal of Hazardous Materials*, **150**, 468-493.

Ruscadella M., (2012), *Treatment of mature urban landfill leachates by Anammox process*, PhD Thesis, University of Gerona, Spain.

Salem Z., Hamouri K., Djemaa R., Alliak K., (2008), Evaluation of landfill leachate pollution and treatment, *Desalination*, **220**, 108-114.

Schroeder P.R., Dozier T.S., Zappi, P.A., McEnroe B.M., Sjostrom J.W., Peyton R.L., (1994), *The hydrologic evaluation of landfill performance (HELP) model. Engineering documentation for version 3. EPA/600/r-94/168b*, Environmental Protection Agency (EPA), Cincinnati, OH, E.E.U.U.

Tatsi A.A., Zouboulis A.I., (2002), A field investigation of the quantity and quality of leachate from a municipal solid waste landfill in a Mediterranean climate (Thessaloniki, Greece), *Advances in Environmental Research*, **6**, 207-219.

Van Passel S., Dubois M., Eyckmans J., de Gheldere S., Ang F., Jones P.T., Van Acker K., (2013), The economics of enhanced landfill mining: private and societal performance drivers, *Journal of Cleaner Production*, **55**, 92-102.

Vergara S.E., Tchobanoglous G., (2012), Municipal solid waste and the environment: a global perspective, *Annual Review of Environment and Resources*, **37**, 277-310.

Visvanathan C., Karthikeyan O.P., Park K.H., (2011), Sustainable landfilling in tropical conditions: comparison between open and closed cell approach, *Waste Management and Research*, **29**, 386-396.

Vose D., (2002), *Risk Analysis: a Quantitative Guide*, 2nd Edition, London: John Wiley & Sons.

Wang H.R., Wang J.H., (2006), Virtual water content of livestock products in China, *Huan jing ke xue= Huanjing kexue*, **27**, 609-615.

Weng Y.C., Fujiwara T., (2011), Examining the effectiveness of municipal solid waste management systems: An integrated cost-benefit analysis perspective with a financial cost modeling in Taiwan, *Waste Management*, **31**, 1393-1406.

Yalili M., Kilic M., Kestioglu K., Yona T., (2007), Landfill leachate treatment by the combination of physicochemical methods with adsorption process, *Journal of Biological and Environmental Sciences*, **1**, 37-43.