Environmental diagnosis methodology for municipal waste landfills as a tool for planning and decision-making process

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Abstract

In Europe, a Council Directive passed in 1999 provided for the regulation of waste disposal in landfills. This was a specific piece of legislation aimed at environmental control of new and currently operational installations. As a result it has become necessary to adapt currently operational release points to make them compatible with the new legislation. This new situation has obliged the different environmental organisations to carry out a stocktaking of release points in order to draw up a Conditioning Plan or a Closing Plan in accordance with the Directive. The present study describes a new methodology by which environmental diagnosis of landfill sites may be carried out, involving the formulation of environmental indexes which give information about the potential environmental problems of currently operational landfills. The indexes provide information related to location, design and operation in order to help draw up action plans for the conditioning or closure of the landfill site and to prioritize the order of actions required.

Keywords: municipal solid waste, landfill, environmental impact assessment, landfill sealing, landfill design, landfill recovering.
1 Introduction

1.1 Environmental impacts of waste landfilling

The increasing quantities, inappropriate treatment and final disposal of waste can result in negative impacts not only to public health and to the environment but also as a result of the social and environmental effects these activities generate [1, 2]. Damage to the environment due to poor waste management can be avoided by implementing environmentally sensitive waste management techniques, involving minimisation, composting, recycling, reuse and waste-to-energy programmes [3, 4]. However, solid waste disposal in landfills remains the usual method of disposal in the vast majority of cases [5, 6].

Landfills were initiated largely as a result of the need to protect the environment and society from adverse impacts of alternative methods of refuse disposal such as open-air burning, open-pit dumping, and ocean dumping [5]. Although they have eliminated some impacts of old practices, new problems have arisen, primarily due to gas and leachate formation. Besides potential health hazards, these concerns include fires and explosions [5, 7], vegetation damage [8], unpleasant odours [9], landfill settlement [10], ground and surface water pollution [11, 12], air pollution [13] and global warming [14].

1.2 The impact of the European Landfill Directive

The European Union Directive 31/1999 for controlling the landfilling of waste was under discussion for many years prior to its publication. The overall aim of the Directive is to prevent or reduce as far as possible any negative impacts on the environment due to the landfilling of waste. In particular, it is concerned with preventing pollution of surface and groundwater, pollution of soil and air pollution. To meet these objectives, several measures are required aimed at improving the design, operation and management of landfills and also at restricting the types of waste that are allowed to be landfilled.

The Landfill Directive was due to be incorporated into the national law of each EU member state by July 2001. Examples of countries implementing the Directive are Spain [15], the United Kingdom [16] and Finland [17].

Member States are obliged to take measures to ensure that landfills which had already been granted a permit or which were already in operation when the Directive came into force, do not continue to operate unless the requirements are met within a maximum of eight years after the date of the legislation. In consequence, environmental organisations have been obliged to carry out a stocktaking of release points located in their territory in order to draw up a Conditioning Plan or a Closing Plan for each site, depending on the environmental problems found in each case. These plans need to include the specific permission conditions listed in the Directive and to outline any corrective measures which the operators consider necessary to comply with the Directive requirements [18]. In the specific case of Spain, the deadline for the Conditioning Plans was the end of 2002; however, it has been shown that 52% of landfills do not yet have a plan [15].
1.3 Methodologies for evaluating waste landfill environmental impact

The first step in applying the Directive is to inspect the landfill sites and to study their environmental impact. This in turn involves carrying out an environmental diagnosis of the landfill to identify the various problems. A number of authors have worked on different methods for evaluating environmental impact in the design plans for new landfills [19], and methodologies have also been developed to study public opinion with regard to the siting of new landfills [20]. These studies are of limited relevance to our research since we are concerned with landfills which are currently in operation. Nevertheless, on the basis of these methods, further methods have been developed to carry out environmental diagnosis in operational facilities, with the aim of resolving particular problems in certain provinces or groups of municipalities. In most cases, these methods involve stocktaking of local natural phenomena in order to compile lists of impacts in the landfills where monitoring was undertaken, but the sphere of application is limited and it is no possible to take decisions about their control, closing, sealing or recovering [15].

Accordingly, we have developed a new methodology with the objective of providing sufficient data to determine the environmental problems generated by waste landfills and to control their operational state. The methodology has already been applied to a large number of landfills and some changes are being incorporated to correct specific shortcomings and to create software that will facilitate application of the methodology.

2 Methodology description

The methodology is based on the use of environmental indexes designed to provide quantitative assessment of the environmental interaction between the release point and potentially affected environmental elements (surface water, groundwater, atmosphere, soil and health). In addition, assessment is made of the environmental value of each environmental element taken into account, as well as of the operational state of the landfill from the environmental point of view [15, 21].

The methodology may only be applied to municipal solid waste landfills classified as non-hazardous waste landfills by the Directive 31/1999 [18]. Territorial application of the methodology may include countries in the European Union and any other country where similar legislation exists, or indeed where there is no legislation or the legislation is less prescriptive than this Directive [15].

2.1 Environmental Landfill Impact Index (ELI)

The methodology obtains a general index called the Environmental Landfill Impact Index [15, 21]. This index characterizes the overall environmental state of the landfill, obtaining values between 0 and 25 with classifications of ‘very high’, ‘high’, ‘average’, ‘low’ and ‘very low’ (Table 1). It is expressed by
eqn. (1), where ERI<sub>i</sub> is the Environmental Risk Index for each environmental element.

\[
ELI = \sum_{i=1}^{5} ERI_i
\]

Table 1: Classification of different indexes.

<table>
<thead>
<tr>
<th></th>
<th>Very low</th>
<th>Low</th>
<th>Average</th>
<th>High</th>
<th>Very high</th>
</tr>
</thead>
<tbody>
<tr>
<td>0≤ELI&lt;5</td>
<td>5≤ELI&lt;10</td>
<td>10≤ELI&lt;15</td>
<td>15≤ ELI&lt;20</td>
<td>20≤ELI&lt;25</td>
<td></td>
</tr>
<tr>
<td>0≤ERI&lt;1</td>
<td>1≤ERI&lt;2</td>
<td>2≤ERI&lt;3</td>
<td>3≤ERI&lt;4</td>
<td>4≤ERI&lt;5</td>
<td></td>
</tr>
<tr>
<td>1≤eVi&lt;1.8</td>
<td>1.8≤eVi&lt;2.6</td>
<td>2.6≤eVi&lt;3.4</td>
<td>3.4≤eVi&lt;4.2</td>
<td>4.2≤eVi≤5</td>
<td></td>
</tr>
<tr>
<td>0≤Pbc&lt;0.2</td>
<td>0.2≤Pbc&lt;0.4</td>
<td>0.4≤Pbc&lt;0.6</td>
<td>0.6≤Pbc&lt;0.8</td>
<td>0.8≤Pbc&lt;1</td>
<td></td>
</tr>
<tr>
<td>0≤Pbc-si&lt;0.2</td>
<td>0.2≤Pbc-si&lt;0.4</td>
<td>0.4≤Pbc-si&lt;0.6</td>
<td>0.6≤Pbc-si&lt;0.8</td>
<td>0.8≤Pbc-si&lt;1</td>
<td></td>
</tr>
<tr>
<td>0≤Pbc-o&lt;0.2</td>
<td>0.2≤Pbc-o&lt;0.4</td>
<td>0.4≤Pbc-o&lt;0.6</td>
<td>0.6≤Pbc-o&lt;0.8</td>
<td>0.8≤Pbc-o&lt;1</td>
<td></td>
</tr>
</tbody>
</table>

2.2 Environmental Risk Index (ERI)

The Environmental Risk Index determines the environmental impact potential for each environmental element, reflecting whether or not interaction exists between the release point or landfill and the characteristics of the environment [15, 21]. It is expressed by eqn. (2), where Pbc<sub>i</sub> is the Probability of Contamination and eV<sub>i</sub> is the Environmental Value, both for each environmental element (<i>i</i>). The index obtains values between 0 and 5 with classifications of ‘very high’, ‘high’, ‘average’, ‘low’ and ‘very low’ (Table 1).

\[
ERI_i = \sum_{i=1}^{5} (Pbc_i \times eV_i)
\]

2.3 Probability of Contamination (Pbc)

The Probability of Contamination for each environmental element depends on the scale of operation, as well as waste characteristics and the spread of disposals in the landfill environment [15, 21]. It may obtain values between 0 and 1 and is classified as ‘very high’, ‘high’, ‘average’, ‘low’ and ‘very low’ (Table 1).

In order to assess contamination probability, a number of landfill variables are selected for each environmental element. All variables have a theoretical justification of their state, which is closely related to the biochemical and physical processes directly or indirectly affecting the environmental elements. The variables are based on guidelines established in the European Council Directive 1999/31/EC and they are classified in two groups: (i) variables related to operation of the landfill (for example, in the case of contamination probability of groundwater, these variables are: compaction, waste and organic matter types,
age of landfill, covering material, waterproofing of release vessel, control of liquid leachate and surface drainage systems); and (ii) variables related to the siting of landfill (for example, in the case of contamination probability of groundwater, these variables are: pluviometry, permeability, release-point localisation in surface runoff, fault, seismic risk, and release-point localisation in flood-water storage volume).

Probability of Contamination for each environmental element is expressed by eqn. (3) where \( n \) is the number of variables affecting each environmental element, \( CRI_j \) is the Contamination Risk Index for each variable \((j)\), \( CRI_{j\text{min}} \) is the minimum value obtained by the CRI for each variable and \( CRI_{j\text{max}} \) is the maximum value obtained by the CRI for each variable.

\[
Pbc_i = \frac{\sum_{j=1}^{n} CRI_j - \sum_{j=1}^{n} CRI_{j\text{min}}}{\sum_{j=1}^{n} CRI_{j\text{max}} - \sum_{j=1}^{n} CRI_{j\text{min}}} \quad (3)
\]

### 2.3.1 Contamination Risk Index (CRI_j)

Evaluation of each variable \((j)\) may be obtained by the Contamination Risk Index \((CRI_j)\) for each variable, whose expression is shown in eqn. (4):

\[
CRI_j = C_j \times W_j \quad (4)
\]

In this expression, \( C_j \) is the classification of the variable and provides information on the situation of the release point or the interaction between disposal processes and environmental characteristics related to the variable \([15, 21]\). The range of values may be 1, 2, 3, 4 or 5.

\( W_j \) is the weighting of each variable. Values may be 1 or 2, depending on the relationship between the variable and the concept of ‘structural elements’ at the release point; the structural elements considered are: the existence of organic matter, humidity and density of wastes. These three concepts participate in the main biochemical and physical processes produced in the release point and cause production of gas and leachate, affecting all variables and providing greater weighting to the different landfill variables \([15, 21]\). For example, the variable ‘leachate control’ affects the environmental elements of surface water, groundwater and atmosphere, obtaining in each case a weighting of 2 since the variable is directly related with the structural element ‘humidity’ and thus with a higher production of leachate, with the consequent risk of contamination.

\( W_j \) also reaches a value of 2 when the variable directly affects the structural elements, although these may not be directly related to the environmental elements. For example, the variable ‘Distance from population point’ contemplates the distance between the landfill and the nearest population point, including isolated settlements, and this affects the environmental element
‘human health’. In this case the variable is directly related with a pollution risk to the health of the inhabitants of the population point.

Justification and classification of the variable ‘Distance from population points’ is shown in Table 2. Classification is carried out on the basis of criteria established by research into congenital and chromosomal [22] anomalies observed in people living near landfills, as well as Spanish legislation concerning hazardous and unsanitary activities and other studies relating the presence of low or high-density population zones near release points to their environmental impact [23]. The same justification and quantification is applied to all the other variables and environmental elements.

Table 2: Classification and weighting of the variable ‘Distance from population points’ for the environmental element ‘human health’.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Justification</th>
<th>Wj</th>
<th>Cj</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfill very close</td>
<td>High-density urban settlement at close distance (under 2 km)</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Landfill close</td>
<td>Rural area with several developments or urban industrial area at close distance (under 2 km)</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Landfill at medium distance</td>
<td>Rural area with disperse developments at some distance (between 2 and 3 km)</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Landfill far</td>
<td>Few and disperse constructions at some distance (between 2 and 3 km)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Landfill very far</td>
<td>No developments in area (over 3 km)</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

2.3.2 Probability of contamination due to landfill site and probability of contamination due to landfill operation

Taking into account the rate expression for Probability of Contamination for each environmental element, two further indexes are obtained. These provide information about the suitability of the location of the landfill and its operational state, and again apply to each environmental element: Probability of Contamination due to landfill site (Pbc-si) and Probability of Contamination due to landfill operation (Pbc-oi). The rate expression used to quantify these indexes is represented by eqn. (4); however, variables included in this expression are restricted to those related to the location of the landfill in the first case, and those related to the operation of the landfill in the second case. The variables may obtain values between 0 and 1 and are classified as ‘very high’, ‘high’, ‘average’, ‘low’ and ‘very low’ (Table 1).

2.4 Environmental value (eV)

The concept Environmental Value is designed to identify and quantify the environmental assessment of each environmental element in the area of the
landfill. The index takes into account the relationship between the landfill environmental and/or social and political characteristics and the emissions in the release point [15, 21]. Values range between 1 and 5 for each environmental element, with classifications of ‘very high’, ‘high’, ‘average’, ‘low’ and ‘very low’ (Table 1).

Table 3: Justification and quantification of the characteristic ‘use of water’ for the environmental element ‘surface water’.

<table>
<thead>
<tr>
<th>A3</th>
<th>Use of water</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Not for use by humans</td>
</tr>
<tr>
<td>2</td>
<td>Irrigation/agricultural</td>
</tr>
<tr>
<td>3</td>
<td>Industrial, recreational, street cleaning, garden irrigation</td>
</tr>
<tr>
<td>4</td>
<td>Drinking water, co-existing with other supply sources</td>
</tr>
<tr>
<td>5</td>
<td>Drinking water, exclusive supply source</td>
</tr>
</tbody>
</table>

In the case of surface water, four characteristics are used to quantify Environmental Value: type of surface water flow ($A_1$), type of surface flow branch line ($A_2$), use of water ($A_3$), existence of animal or vegetable species ($A_4$). The rate expression used to quantify these four characteristics is represented by eqn. (5). Each characteristic may obtain values of 1, 2, 3, 4 or 5 and some may acquire a weighting coefficient value of 2 due to their relative importance; for example, the characteristic ‘use of water’ has a weighting coefficient of 2 in the case of the environmental element ‘surface water’. Table 3 shows justification and quantification in the case of the characteristic ‘use of water’. The same justification and quantification is applied to the other characteristics and environmental elements.

$$eV_{surface\text{water}} = \frac{A_1 + A_2 + 2 \times A_3 + A_4}{6}$$  \hspace{1cm} (5)

3 Summary of results

The methodology described makes it possible to carry out an environmental diagnosis of urban waste landfills providing sufficient data to determine the set of environmental problems posed by each landfill. The results obtained, formulated in a series of environmental indexes, may be used in various ways: (i) as a tool for studying the suitability of landfill sites and for monitoring their operation; (ii) for application in the development of projects aimed at conditioning landfills with the objective of continuing their use with reduced environmental impact and in accordance with the new legislation; and (iii) for application in closing, sealing and reinsertion projects in cases where termination of landfill operation is required. The information provided by each index is summarized below.
3.1 Environmental Landfill Impact Index (ELI)

This index provides information regarding the overall set of environmental problems posed by the landfill. Applied to different landfills in the same study area, the ELI can be used to draw up lists of priority actions. Landfills with greater ELI values would receive higher priority of action since they pose greater environmental problems.

3.2 Environmental Risk Index (ERI)

Once the overall set of environmental problems posed by the landfill has been determined by means of the ELI, the ERI for each environmental element may be studied. For each landfill, the ERI indicates which environmental element or elements are most affected by the presence of wastes, making it possible to determine the extent of deterioration in each case.

3.3 Environmental Value (eV)

The eV is considered as a relative environmental value, since it aims to identify and quantify the relation between the environmental and socio-political characteristics of the landfill and the landfill emissions, as well as the environmental importance of each element in the surroundings of the landfill. The eV thus provides information concerning the suitability of the landfill location.

3.4 Probability of Contamination (Pbc)

This concept calculates the greater or lesser risk of impact for each environmental element owing to the location and/or operation of the landfill. The difference between the Probability of Contamination and the Environmental Risk Index is that in the first case, risk of environmental impact of the landfill is calculated without taking into account the environmental value of the area in which the landfill is situated. Two landfills with the same contamination probability (for example 0.5) for an environmental element might obtain two different contamination risk indexes (for example 2.5 -average- and 0.5 -very low-) because they have different environmental value for this environmental element (5 and 1 respectively).

By means of the two types of Pbc it is possible to determine how the location and scale of operation of the landfill intervene in the overall set of environmental problems. In turn, this may help to establish the guidelines which need to be followed for their solution.

Finally, individual analysis of the contamination risk indexes obtained for each variable provides information concerning the actions which need to be carried out in the conditioning or closure and plans. For example, it may be necessary to improve control of leachates or biogas, or to construct facilities for the collection of surface runoff, etc.
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References


