Landfill design using simplified risk assessment procedures

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Abstract

In most of the developing countries, landfilling is the first (and sometimes the only affordable) step for the expansion of Waste Management Systems. Although, in general terms, landfills are considered as relatively simple technological systems with well-established knowledge of their environmental impacts, their design, construction and operation is not always an easy and standardized issue. Especially in developing countries, limited financial resources, lack of institutional development, poorly developed technical capabilities and lack of the necessary data (waste quantities and composition, geological, hydrogeological and climatic data) for designing a landfill, are usually the main barriers that do not allow environmentally sound solutions to landfilling problems. The only way to succeed at landfill design and at the same time to be in accordance with the context of opportunity cost is to relax the landfill standards, when this is possible, without unduly affecting protection of the environment. Significant efforts have been implemented for this issue, mainly from ISWA Landfill Working Group and South African experts. A simplified risk based approach is used in order to identify the parameters that mainly affect the conceptual design of leachate management. The design that is proposed is based on the sensitivity of the surrounding environment. The proposed methodology works with limited and easy to access data and at the end of the procedure it provides the constituents of the technical design for leachate management. Thus it can be easily linked with cost issues. The whole procedure aims to provide a simple and effective decision making tool for landfill designers in developing countries, as well as a measure to check environmental impacts of current landfills or dumpsites.

Keywords: landfill design, risk assessment, leachate management, risk-based engineering.
1 Introduction

Risk assessment has usually been applied to two major areas:

a. Adverse health and environmental effects of exposure to hazardous chemicals.

b. Failure of complex technological systems.

The use of risk assessment in waste management facilities and especially in landfills has been increased since it was understood that landfills cover both of the previous areas. Landfills are transformed to complex technological systems, since the use of liners, leachate and biogas collection and treatment equipment has been generalised. At the same time all landfills, especially hazardous waste landfills, can result in serious environmental and health effects due to both construction and operational problems.

The more modern landfill experiences are cumulated, the more risk assessment procedures are involved in almost all levels of a landfill life cycle. Risk analysis can assist in the development and/or change of waste management regulations. In the US and UK, risk assessment procedures are strongly related to waste management licensing [1,2]. Regarding site allocation a preliminary risk assessment provides decision-makers with useful data that allows to select where the procedure should continue or stop.

The risk involved with contaminant releases from landfills or uncontrolled dumps is another scientific area that risk assessment has been widely used. Risk analysis can support decision-making on establishing priorities in remediation activities as well as selecting remediation alternatives for individual contaminated sites [3]. For modern landfills, such as those that conform to high environmental performance standards, risk assessment procedure need to encompass considerations of failure of landfill technology as well [4]. In landfill designing, the understanding of the physical-chemical and mechanical characteristics of the materials used is of major importance. Principles of risk assessment are applied not only to the overall design but also right down to the detail of individual materials and their methods of installation [5]. In developing countries, simplified risk-based methodologies have been developed in order to provide the necessary Minimum Requirements of a landfill, in terms of conceptual design [6,7]. Waste acceptance criteria are also developed with the use of risk–based procedures, for different types of disposal facilities [8,9].

The purpose of this paper is to present a simplified risk based engineering approach for leachate management, especially for landfill design in developing countries. This approach can work as a good decision making tool for landfill designers, by providing the conceptual technical design and the necessary constituents of leachate barriers.

2 The framework for risk based engineering in landfills

Within this approach the source-pathway-receptor concept holds a key position. The ‘source’ for waste management facilities is defined by the hazardous properties of the waste types and operations to which they will be subjected on
the proposed site. The environmental ‘receptors’ (or targets’) are those entities, which are liable to be adversely affected by the identified hazards transferred from the defined ‘source’ into the environment by the identified ‘pathways’. ‘Pathway’ is the mechanism by which the receptor and source can come into contact. Modern landfills are characterized by the multi-barrier concept, meaning that for every possible emission to the environment several barriers are developed. The containment engineering for a landfill is essentially the mitigation for the site’s risk to the environment. Thus containment engineering serves as a pollution prevention system: the ‘source’ of pollutants (leachate, gases) is blocked by leachate and biogas collection and treatment equipment and the link with a possible ‘pathway’ (and consequently with a ‘receptor’) is impossible. Fundamental to environmental risk assessment is the conceptual model stage, which enables a clear picture to be established of the site and its environment, based upon the nature of the site and its environmental situation [10].

3 Leachate management concept

It is assumed that the main risk from a leachate leak is the groundwater pollution. This assumption fits with the advanced needs for integrated water resources protection and management that characterize a large part of developing countries. The potential for groundwater pollution can be defined as follows [2]:

\[ P_{gw} = (LR) \cdot (WC) \cdot (TC) \]  

(1)

Where:

- \( P_{gw} \) is the Potential groundwater pollution.
- \( LR \) is the Likelihood of Release for the produced leachate.
- \( WC \) is the Waste Characteristics.
- \( TC \) is the Target Characteristics.

All of these parameters are discussed in the following sections.

3.1 Likelihood of release

Likelihood to release (or potential to release) is the magnitude that expresses the possibility of a hazardous substance release. For groundwater, USA EPA has suggested the following expression to estimate Likelihood of release:

\[ LR = Cf \cdot (NP + DA + TT) \]  

(2)

Where:

- \( Cf \) is the containment factor.
- \( NP \) is the net precipitation.
- \( DA \) is the depth to aquifer.
- \( TT \) is the travel time through the surrounding media, depending on hydraulic conductivity.

Containment factor \( Cf \) represents the natural or artificial protection that is provided against the leachate leakage. Usually, containment factor may range
between total containment (dry-tomb landfill) to attenuation and disperse landfills. Although this is a very critical point to risk assessment procedures, in this paper containment factor is not considered for two reasons. Firstly, the application of this paper starts after the landfill location has been decided. That means that the designer of the landfill already knows if natural containment do exist and if groundwater protection is necessary. Secondly, one of the main objectives of this paper is to provide a decision support tool in order to identify if artificial liner is necessary. So the selection of the type of containment is to be defined, according to the rest of the parameters.

Regarding the Net Precipitation, it is preferable to be replaced by the Climatic Water Balance. The Climatic Water Balance is not a detailed classical water balance, such as one that would be used to determine ground water recharge. It is a simple calculation that assists in deciding whether leachate management is required or not. It therefore provides a conservative means determining whether or not significant leachate generation will occur. The Climatic Water Balance (B) is calculated using only the two climatic components of the full water balance, namely Rainfall (R) and Evaporation (E) [11, 12], as follows:

\[ B = R - E \]  

(3)

Where:
B is the Climate Water Balance in mm of water.
R is the rainfall in mm of water.
E is the evaporation from a soil surface in mm of water.

A first case is if B is positive for less than one year in five for the years for which data is available. If so leachate management system may not be necessary, especially if other important factors (waste moisture, groundwater protection etc.) lead to the same direction. At this case, the site is classified as a B- site. Otherwise, if B is positive for more than one year in five for the years, for which data is available, the site is classified as a B+ site and leachate management systems are necessary.

Finally, regarding the Depth of the Aquifer and the Travel Time, since the design process starts after the final site allocation, these parameters are set and they are the same for every alternative design that does not affect the containment factor.

3.2 Waste characteristics

This paper deals only with Municipal Solid Waste Landfills. Thus, the source characterization depends on two parameters: the landfill size and the biodegradable fraction of the waste. In general terms, the following equation is used to estimate WC:

\[ WC = (Q) \cdot (C) \]  

(4)

where:
Q is the amount of waste in the Landfill.
C is the concentration of hazardous substances in waste.
Taking into account that the amount of waste is directly related to landfill size, parameter Q can be substituted by the size of the landfill. All landfills grow in size with the passing of time. The major characteristic that affects the operation of a landfill and, therefore, the need for facilities, plant and operating skills is the rate of deposition of waste. However, the final size of a landfill will determine its long-term pollution potential. The classification system is based on the Maximum Deposition Rate (MDR), meaning the maximum quantity of waste that will be disposed of in a year during landfill’s lifetime. Landfills are characterized as [11,12]:

a. Small (S), when the MDR is less than 5,000 tons per year. That size corresponds to 30,000 inhabitants, with a daily production around 0.5 kg/(capita and day). Practically, this is the case for the majority of rural areas.

b. Medium (M), when the MDR is between 5,000 and 100,000 tons per year. Practically, that size corresponds to 400,000 inhabitants, with a daily production around 0.7 kg/(capita and day). This is the case of a served area that consists of rural as well as urban populations.

c. Large (L), when the MDR is over 100,000 tons per year, corresponding to 320,000 inhabitants of an urban area, with a daily production of 0.85 kg/(capita and day).

Regarding the concentration of the hazardous substances in waste, only Municipal Solid Waste is considered, thus the main pollutant generator is the biodegradable organic fraction of the waste. That means that the parameter C can be replaced by another parameter that represents the biodegradable fraction of the waste.

For the purpose of the classification system, waste will be classified according to its biodegradable fraction (garden and food waste, paper) like this:

a. If the biodegradable fraction is over 20% dry mass, then waste will be classified as H (meaning High biodegradable fraction).

b. If the biodegradable fraction is less than 20% dry mass, then waste will be classified as L (meaning Low biodegradable fraction).

The dividing point of 20% of biodegradable waste is tentative at present. It should be underlined that the previous concern only municipal solid waste, exclusively.

### 3.3 Target characteristics

The majority of decisions on standards of design and construction of landfills depends upon the level of groundwater protection that is necessary. Several approaches are available in order to determine the level of groundwater protection needed (Pl) and to classify groundwater aquifers and surface water bodies [13]. In general terms, the following criteria are used:

a. The quantity of water that could be abstracted (the “potential sustained yield”).

b. The quality of water.

c. Whether or not that aquifer is needed (“significance”).

Three basic levels of required protection are considered [13,14]:

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a. Minimum (G1): where the groundwater is unsuitable for human or agricultural use, where its degradation will not unacceptably impact on the local ecology or where the local climate will prevent the generation of leachate from any landfill.
b. Intermediate (G2): for which an attenuate and disperse design may be sufficient.
c. Maximum (G3): for which full containment design is necessary.

3.4 Selection of critical parameters

According to the previous analysis, taking into account that site specific factors are given since the location is identified, it is obvious that eqn (1) can be transformed in eqn (5):

\[ P_{gw} = C_f \cdot (B + K_o) \cdot (MDR \cdot B_f) \cdot (P_l) \]  \hspace{1cm} (5)

Where:
- \( C_f \) is the containment factor.
- \( B \) is the Climatic Water Balance (values: B+, B-).
- \( K_o \) is the constant sum of TT+DA (eqn 2).
- \( MDR \) is the Maximum Deposition Rate (values: S, M or L).
- \( B_f \) is the Biodegradable fraction indicator (values: H or L).
- \( P_l \) is the groundwater protection level (values: G1, G2, G3).

So, the potential for groundwater pollution is a function of \( B, MDR, B_f \) and \( P_l \). Assuming that parameter \( B_f \) is always H (safe estimation), the potential for groundwater pollution (and consequently the leachate management design) can be estimated like the following:

\[ P_{gw} = C_f \cdot K_1 \cdot (B + K_o) \cdot (MDR \cdot P_l) \]  \hspace{1cm} or,  
\[ \frac{P_{gw}}{C_f} = K_1 \cdot (B \cdot MDR \cdot P_l) + K_1 \cdot K_o \cdot (MDR \cdot P_l) \]  \hspace{1cm} (6)

Where \( K_1 \) is a constant corresponding to High (H) biodegradable fraction.

Eqn 6 provides some very useful ideas. Since the site location is known and the scope of work is to find an effective design, the natural containment factor is something that is also a constant. Thus the quotient \( P_{gw}/C_f \) can be considered as the real risk for groundwater pollution, if no artificial containment measures should be taken.

This quotient is a function of two products (\( B \cdot MDR \cdot P_l \)) and (\( MDR \cdot P_l \)). Each one of them has a separate contribution to what was mentioned as real risk. Product 1 (\( B \cdot MDR \cdot P_l \)) represents the combined effect of Water Balance, Size of Landfill and Groundwater Protection level, while Product 2 (\( MDR \cdot P_l \)) represents the effect of only the latter two.

As a result it seems that even with a negative water balance, the increase of the size of the landfill and/or the increase of the necessary groundwater protection level increase the real risk for groundwater pollution. Thus, protection measures against groundwater pollution have to be taken in some cases independently of the water balance. The logical consequence of the previous analysis is that conceptual design should be confronted as a process that
increases the artificial protection measures against groundwater pollution as Products 1 and 2 go higher. By this way, the value of the containment factor will be increased and the real risk will be reduced.

4 Results and discussion

Table 1 presents the influence of classification in leachate management. As it is shown at Table 1, the separate components of leachate management systems, such as leachate collection system, liners, leachate treatment etc. are directly related to the risk classification of the landfills. Table 1 provides an easy-to-use tool for the conceptual design of leachate management systems.

As it is obvious from Table 1, the minimum requirements for leachate management are strongly related with the specific features of each site and the corresponded groundwater risk. The reliability of the resulted conceptual design and its effectiveness in environmental terms depends on the reliability of the utilized parameters and the certainty that corresponds to them, as in every decision-making system. But by having the sites allocated and some basic data for them, Table 1 provides a good point to start the decision-making regarding the capital cost of each one, according to the available financial resources. On the other hand, a lot of decisions cannot be faced on a macro-level and due to this reason there are a lot of “O” symbols in Table 1. “O” symbol means that the specific component may not be included within conceptual design but this has to be decided only having the knowledge of the local conditions. So Table 1 cannot substitute the site–specific design, in any way.

As it can be shown at Table 1 the reduction of the water entering the site from surface runoff and the estimation of the unsaturated zone beneath the landfill are necessary to almost every type of landfill. So these two measures can be easily set as minimum requirements for leachate management. The need for a low permeability cap is also necessary to a lot of landfill types, although it is more directly related to the water balance parameter and to the size of the landfill. At 10 of the 18-landfill types, liners deem to be a necessity and the same goes for groundwater monitoring facilities. Of course, whenever a liner does exist, a leachate collection system is also considered as a non-alternative option and at least a recirculation system and a collection pond should be constructed. On the other hand leachate treatment (other than recirculation) seems to be a requirement only for 3 types of landfills, while in a lot of cases the necessity for a leachate treatment facility depends upon local conditions, which cannot be determined in this paper.

It should be noticed that in Table 1, as the risk goes higher the protection measures go more complicated and expensive also. This general rule has some exceptions in landfills G2SB+, G3SB+, G2MB+, G3MB+ where protection measures make a peak. All of these cases have more than intermediate groundwater protection and positive water balance.

Another way to utilize Table 1 can be found when a comparison of different sites has to be made, during site allocation efforts. In stead of looking for the conceptual design depending on the landfill characteristics (groundwater
protection, water balance and size) and the relative risk, someone can read the table looking for the characteristics that have to be preferred in order to have low capital cost (and operational) cost for the necessary landfills. By this way Table 1 can be utilized in order to provide ready to use data for a comparative analysis of different proposed sites and cost-benefit analysis for alternative designs.

Table 1 may have one additional use. It can provide a good evaluation tool for the current landfills. Normally these landfills range between uncontrolled landfills and what is called “engineered” or “semi-controlled” landfills in most of the developing countries. Table 1 can provide some improvements that have to be made in these landfills in order to increase environmental protection. In case these improvements are cost-effective and easy in terms of construction, then the specific landfills may be seriously upgraded. Otherwise, this may be the case of a landfill that has to be closed directly.

5 Conclusion

Based on an already existing classification scheme and some well-defined parameters, a new approach is presented at this paper: a risk approach to leachate management conceptual design. The real effort, at this point, is to set out different Minimum Requirements according the landfill characteristics. This approach should be considered as an assessment tool, which classify relatively the landfills according their risk for groundwater, rather than an absolute quantified scale that provides a certain risk for each landfill. Consequently, a decision – making system is presented in order to help the landfill designer to select the necessary components of the leachate management system.

The risk classification of the landfills is based on three parameters:

a. The groundwater protection level.
b. The size of the landfill.
c. The Climate Water Balance.

One major output of the system is that groundwater potential pollution is more sensitive to landfill size and groundwater protection level, than to the Climate water balance.

The risk classification of the several types of landfills and the Minimum Requirements of Table 1 that resulted should be faced, as semi-empirical or practical guidelines that cannot substitute the specific studies, needed in every case. They will serve more as guidance for the designers rather than an absolute or certain way to design a landfill, and of course, the application of this guidance presupposes the deep knowledge of the local conditions, since every single landfill is a unique case.

There are several ways to utilize the risk classification of the 18 types of landfills and the corresponding conceptual design. These include conceptual design, site allocation procedures, evaluation of current landfill practices and improvements in current landfills.
### Table 1: Leachate control measures according the classification system.

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<th>Protection measures - cost</th>
<th>Risk</th>
<th>LANDFILL TYPE</th>
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**Protection measures - cost**

**Risk**

**LANDFILL TYPE**

X: specific measures have to be taken for the specific type of landfill.

O: specific measures has to be established only if local conditions are favorable.

*: treatment other than recirculation

**: Piping system or drainage blanket. Whenever a leachate collection system tick (X) exists without leachate treatment tick, recirculation is the only leachate treatment.
References