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A Methodology for Assessing the Potential Environmental Impact of Failure of Leachate-Retaining Earthen Dams

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Abstract

We describe herein a useful model for assessing the environmental impact of the breakage of earthen dams used to retain leachate fluids. To create this model, we analyzed three parameters: (1) the characteristics of both the earthen dam and the leachate; (2) the behavior of the leachate cascade resulting from breakage of the dam; and (3) the environmental effect of the resulting pollution. To accomplish this, we first analyzed the failure of earthen dams for leachate according to the Dam Break Inundation Analysis methodology, which provides the characteristics of the leachate cascade or avalanche resulting from the dam breakage. We then used data for different earthen dams for leachates and calculated the volume of leachate that would reach each point the leachate-flow bed downstream of the dam to generate a graph identifying areas at risk from the leachate cascade. As a third step, we calculated the pollutant charge of leachate, and lastly identified and assessed the environmental factors (EFs) within the risk area. Through these steps we formulated an equation for the environmental risk index (ERI EF), which quantifies the potential environmental impact of the rupture of an earthen dam for leachate on the area surrounding such a dam, and which has a value that ranges from 0 to 1. In order to validate this methodology, we applied the ERI EF equation to nine man-made earthen dams for leachates. All nine are considered safe facilities in having had no accidents in the years since their construction. All have ERI EF values below 0.12, indicating that this value can serve as an appropriate guide to the environmental impact of the rupture of earthen dams that retain leachates.

Key words: environmental factor, pollutant charge, toxic liquid, leachate, DAMBREAK, environmental impact, environmental risk, rating curves

Introduction

VARIOUS TYPES OF DANGEROUS liquids, including leachates from landfills and composting plants, municipal waste water, and industrial waste water, are often contained by earthen dams, and therefore present a considerable environmental risk in case of the breakage of such dams.

Leachates are complex mixtures of inorganic and organic components, and this factor, combined with the specificity of their location, often means that in the case of their escape from an earthen dam, the route of environmental exposure and resulting toxicity to the environment remain unknown. However, such an event poses a public health hazard, since the migration of pollutants could compromise groundwater and surface water sources (Arneth *et al*., 1989; Christensen *et al*., 2001; Koshy *et al*., 2007). In fact, leachates can constitute the main source of pollution in both groundwater and surface water (Ding *et al*., 2001; Flyhammar, 1997; Hancock *et al*., 1995; Isidori *et al*., 2003).

In the case of breakage of an earthen dam used to contain leachates, the leachate liquid would form an avalanche or cascade that would advance along the line of maximum slope of the land around the dam, with a significant environmental impact. This makes it necessary to take maximum precaution in the management of such dams.

The magnitude and intensity of the potential environmental impact of the breakage of an earthen dam retaining leachate depends on three parameters: (1) the structural characteristics of the dam; (2) the flood of toxic leachate liquid resulting from the dam breakage; and (3) the sensitivity of the environmental factors (EFs) in the medium receiving the leachate flood.

The following geometric characteristics of an earthen dam determine the potential for a leachate avalanche:

- Morphology of the dam and type of break (overtopping, break in piping, etc.).

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- Magnitude of the maximum discharge of leachate upon breakage of the dam, as determined from the dam shape and dimensions of the breach, and the depth and volume of the leachate liquid retained behind the dam.
- Time required for the breach to develop (elapsed time).
- Geometry of the dam, including the morphology of the dam embankment, construction materials used in the dam, depth and height of the dam, width of the crest of the dam, and the factor(s) responsible for the dam failure.

Approximately 50% of earthen dam failures happen during the first 5 years of the dam's life, and 19% occur during the first filling of the reservoir behind the dam (Middlebrooks, 1948). The failure can have four types of origin (Dam Safety Engineering Program, 1994; Dam Safety Engineering Program, 1999; Dam Safety Office, 1992; Fell *et al*., 2003; Ohio Department of Natural Resources, 1994; U.S. Department of Agriculture Soil Conservation Service Engineering Division, 1985), as follows: (1) overtopping, in which the level of the liquid held back by the dam exceeds its maximum limit; (2) piping effect, in which the level of the liquid behind the dam can be considered to be normal; (3) structural failures, such as cracks, settlements, and small slidings of dam-construction materials across one another; and (4) combinations of any of the foregoing causes, including the possibility of a complex correlation among the three types of failure.

A study of earthen dams found that 25% of breakages were due to internal erosion of the dam and/or its foundations, 13% originated from leaks and consequent piping, 15% were due to instability of the dam embankment and subsequent sliding, 5% were caused by damage to the impermeable membrane upstream of the dam embankment, and 12% were caused by a combination of one or more of these factors. The reasons for the remaining breakages are unknown (Dam Safety Office, 1992).

In addition to recognizing the foregoing sources of dam breakage, it is necessary to analyze the liquid retained by an earthen dam, since the chemical and biological complexity of this liquid can identify different methods for its treatment (Bessada *et al*., 1993; Guyonnet *et al*., 1998; Heavey, 2003; Johannessen and Boyer, 1999; Manga and Maury, 2004). Furthermore, the leachate released into the environment by breakage of an earthen retaining dam can affect the EFs located in the resulting flood bed to different degrees.

In addition to their effects on the ground, leachates can have a considerable impact on the atmosphere through the release of methane, CO_2, hydrogen sulfide, chlorinated hydrocarbons, and other potentially toxic substances, some of them highly volatile (Econs SA, 2003; Gandolla *et al*., 1998; El-Fadel *et al*., 1997), and through the generation of odors. The threat to surface water and groundwater from the escape of leachate is also very important, because it can seriously affect human and animal health. Consequently, an exhaustive hydrological and hydrogeological study must be made of the area into which a leachate liquid might escape. Vegetation growing in the flood-bed of the leachate has to be identified in order to study its sensitivity to the leachate, since some leachate liquids can be phytotoxic or affect some species of plants and trees (Alloway and Jackson, 1991; Job *et al*., 1991; Peverly *et al*., 1995; Chan *et al*., 1999; Duggan, 2005; Toribio and Romanyà, 2005).

On the basis of these considerations, the main purpose of this paper is to establish a new model for assessing the environmental risk, in terms of EFs, posed by the breakage of earthen dams for retaining toxic liquids. According to this model, an earthen dam used for this purpose can be considered safe if its ERI EF value does not exceed a certain maximum. If the ERI EF value exceeds this maximum value, various preventive and corrective measures must be applied to the dam during its design, construction, or management.

General Description of the Model

The general scheme for calculating the ERI EF value for an earthen dam is shown in Figure 1. The following three objectives must be met in order to develop the ERI:

- First, the characteristics of the flood created by the escape of toxic leachate must be known, so that the area at risk can be determined according to the volume of leachate that reaches different locations in the flood bed of the leachate. We chose the DAMBREAK Inundation Analysis methodology technique for calculating the characteristics of this flood, and selected Spain as the territory in which we applied it because of the readiness with which we could obtain data about Spanish earthen dams for leachates through visits to and contact with the managers of these facilities.

  The purpose of the DAMBREAK methodology is to simulate the probable effects of a dam failure so as to ensure that loss of life and environmental damage are minimized through appropriate advance warning. Because of the relatively low volume of leachates retained behind earthen dams, the DAMBREAK technique analyzes only the environmental damage done by a dam failure. The steps in the DAMBREAK methodology are: (1) determination of the probable extent of the leachate flood wave; (2) selection of dam-failure scenarios; (3) identification or creation of the failure-event conditions (dam level, hydrographic data,

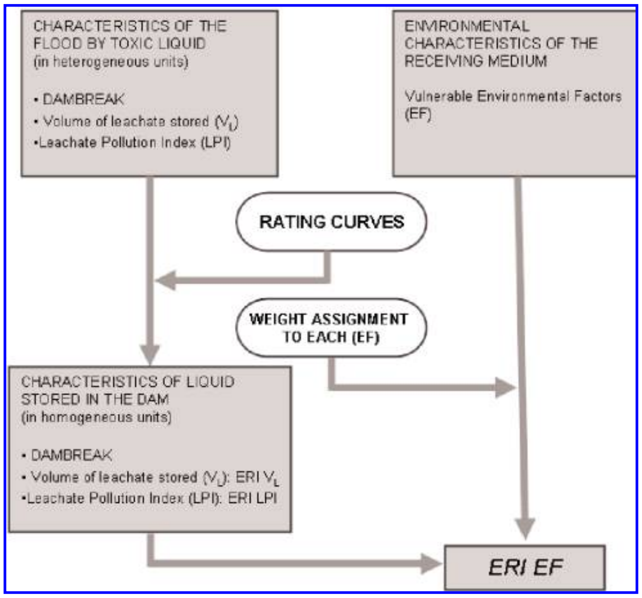

FIG. 1. General scheme to calculate the ERI EF.

etc.); (4) determination of the mode of dam failure and the time over which the failure occurs, based on dam dimensions and composition; (5) collection of terrain data for all areas affected by the dam failure; (6) simulation of the flood wave that would be released downstream by failure of the dam; and (7) creation of maps showing the areas that would be flooded if the dam were to break, and the time at which the wave of leachate released by the break would arrive at each area (Fread, 1987; Froelich, 1987; MacDonald and Langridge-Monopolis, 1984; Dam Safety Office, 1992; Dam Safety Engineering Program, 1994; Ohio Department of Natural Resources, 1994).

Other essential data for calculating the ERI EF are the pollutant charge of the leachate liquid, since the greater this is, the greater will be its toxicity and therefore the greater the environmental impact of the leachate release. The pollutant charge depends on the chemical and biological composition of the leachate.

- Second, the leachate has to be analyzed and its toxicity or pollutant charge calculated, since its environmental impact may be major or minor, depending on the quantity and quality of the leachate.
- Third, the EFs located in the flood bed receiving the leachate, and their sensibility to it, have to be identified and assessed.

Characteristics of the leachate flood according to the DAMBREAK methodology

Once the parameters described above have been established, the DAMBREAK methodology provides the maximum discharge volume and volume of leachate that reach each point on the flood course below the site of an earthen dam break, the path followed by the leachate flood, the classification of the downstream risk from the leachate, and a map of the flooded area (Fig. 2).

The first data needed for using the DAMBREAK methodology are the geometric characteristics of the breach in the dam embankment. According to the U.S. National Weather Service (NWS) and the U.S. Army Corps of Engineers (COE), the length of a breach typically ranges from 0.3 to 0.5 times the height of the dam. The gradient of the breach (ranging from vertical to 1H:1V) depends on the material from which the dam embankment is constructed. The time over which breakage occurs can range from 0.1–2 hours (NWS) to 0.5–4 hours (COE). The most rapid breakage occurs with cohesionless and easily eroded materials.

Froelich (1987) and MacDonald and Langridge-Monopolis (1984) established the existing relationship between the volume of material eroded in the breach of a dam and the breach formation factor (BFF) as follows (Fig. 3):

$$\mathrm{BFF} = \mathrm{V_w}\ (\mathrm{H}) \tag{1}$$

where $\mathrm{V_w}$ represents the volume of liquid stored in the dam (in acre-feet) and H is the height of liquid (in feet) above the base elevation of the breach. The volume of material that is eroded in the breach in cubic yards (V_m, yds^3) depends on the material of which the dam is made, as follows:

$$V_m = 3.75 \cdot (BFF)^{0{,}77}\ \text{(cohesionless materials)} \tag{2}$$

$$V_m = 2.50 \cdot (BFF)^{0{,}77}\ \text{(erosion resistant materials)} \tag{3}$$

The shape of the breach ranges from trapezoidal to rectangular, depending on the material. If the breach is rectangular ($\mathrm{Z_b} = 0$) the gradient of the breach is 90°:

$$W_b = \frac{27 \cdot V_m}{H \cdot (C + H \cdot Z_3/2)} \tag{4}$$

For a trapezoidal breach in a dam with a slope of 45° ($\mathrm{Z_b} = 1$):

$$W_b = \frac{27 \cdot V_m - H^2 \cdot (C \cdot Z_b + H \cdot Z_b \cdot Z_3/3)}{H \cdot (C + H \cdot Z_3/2)} \tag{5}$$

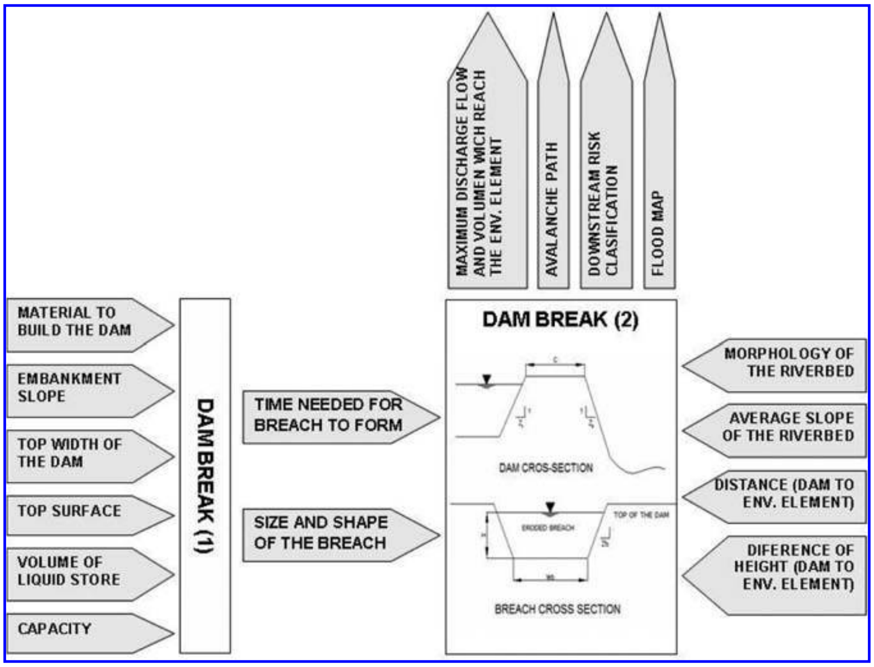

FIG. 2. Scheme to apply to develop the DAMBREAK methodology.

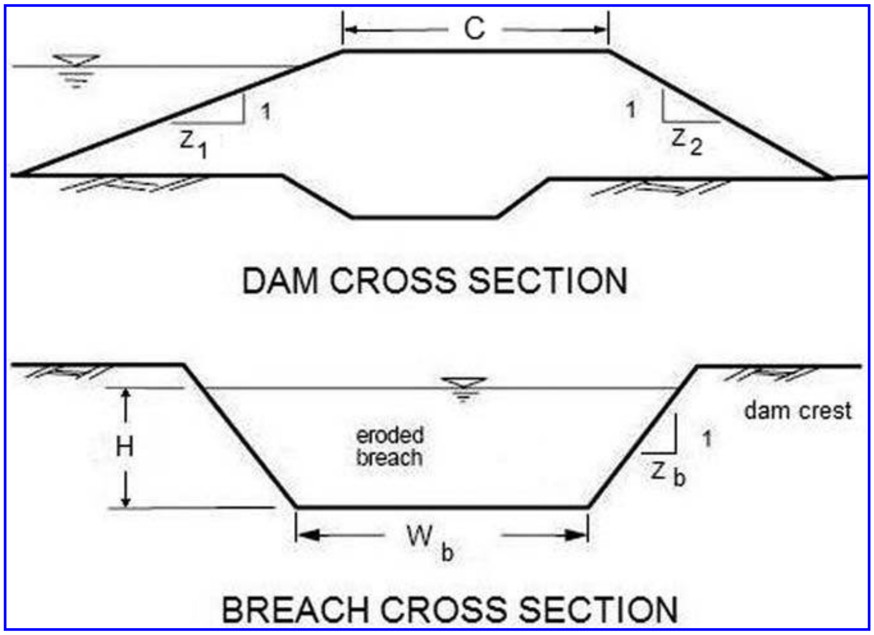

FIG. 3. Dam cross section and breach cross section.

where:
W_b = width of the breach at the base elevation of the breach (in feet)
C = crest width of the dam (in feet)
$Z_3 = Z_1 + Z_2$
Z_1 = slope $(Z_1{:}1)$ of the upstream face of the dam
Z_2 = slope $(Z_2{:}1)$ of the downstream face of the dam

The elapsed time in hours (τ) for breach development has been related to the volume of eroded material (V_m) as follows:

$$\tau = 0.028 \cdot V_m^{0.36} \text{ (cohesionless materials)} \tag{6}$$

$$\tau = 0.042 \cdot V_m^{0,36} \text{ (erosion-resistant materials)} \tag{7}$$

For very small dams, the breach-development time is about 10 minutes for cohesionless materials and 15 minutes for erosion-resistant materials (Dam Safety Office, 1992; Dam Safety Engineering Program, 1994; Ohio Department of Natural Resources, 1994).

Estimation of the peak discharge for a dam breach is computed as follows (Fread, 1981):

$$Q_p = 3.1 \cdot W \cdot H^{1.5} \cdot \left[\frac{A}{A + \tau \cdot \sqrt{H}}\right]^3 \tag{8}$$

where:
Q_p = dam breach peak discharge (cfs)
W = average breach width (in feet):

$$W = W_b + Z_b \cdot H \tag{9}$$

H = initial height (in feet) of liquid above the base elevation of the breach:

$$A = \frac{23.4 \cdot S_a}{W} \text{ (10), and}$$

S_a = surface area of the dam (in acres) at the reservoir level corresponding to the depth H.

The next step in the DAMBREAK methodology is to assess the downstream routing of the leachate flood resulting from the dam break. Flood routing is the term used to describe the movement of a flood wave as it traverses a reach of channel. Of interest in flood routing are the reduction of the peak discharge as it moves downstream (attenuation); the travel time of the flood peak between points of interest; the maximum height of the flood liquid at points of interest; and the change in shape of the flood hydrograph as the flood moves downstream. These effects are governed by factors including the slope of the channel bed; the cross-sectional area and geometry of the main channel and overbank areas; the roughness of the main channel and overbank; the potential for storage of flood fluid in off-channel areas separated from areas of active flood-fluid conveyance; and the shape of the flood hydrograph as the flood enters the channel reach. Computational schemes that can account for the physical characteristics of the channel reach and the hydrodynamics of flood-wave movement are best suited for determining the routing of dam-break floods (Dam Safety Office, 1992). A simplified procedure suitable for many planning purposes has been developed by the U.S. Bureau of Reclamation (USBR, 1998) on the basis of observed dam failures, and is the foundation for the development of generalized flood-attenuation curves. The attenuation is described in terms of the dam break peak discharge (Q_p) at the dam site and the peak discharge (Q_x) at some distance downstream from the dam.

The last step in the DAMBREAK methodology is development of the inundation map, which provides a description of the area of flooding that would result from the dam break. The inundation map should also identify zones of high-velocity flow and depict inundation for representative cross-sections of the channel:

$$A = Q_x/V \tag{11}$$

where:
A = cross-sectional area (in square feet) of the channel and overbank needed to pass the flood
Q_x = flood peak discharge (cfs) at location x

Table 1. Chosen Data of the Morphology of the Dam

Volume of leachate (m^3)	*Top surface (m^2)*	*Volume of leachate (m^3)*	*Top surface (m^2)*	*Volume of leachate (m^3)*	*Top surface (m^2)*
15000 (capacity = 20000 m^3)	10000	5625 (capacity = 7500 m^3)	6000	750 (capacity = 1000 m^3)	800
	7500		4500		650
	6000		3000		450
	5000		1750		375
	4000				
	3000	3750 (capacity = 5000 m^3)	4000	563 (capacity = 750)	650
13125 (capacity = 17500 m^3)	10000		3000		550
	7500		2000		450
	5000		1250		300
	3000				
	2750	1875 (capacity = 2500 m^3)	1500	375 (capacity = 500)	400
11250 (capacity = 15000 m^3)	9000		1000		350
	6000		850		300
	4500		700		250
	3000				
	2500	1500 (capacity = 2000 m^3)	1500		
			1000		
			750		
			600		
7500 (capacity = 10000 m^3)	8000	1125 (capacity = 1500 m^3)	1250		
	6000		1000		
	4000		750		
	2000		500		

V = representative average velocity of the flood (in feet per second).

The inundation map should represent a conservative estimate of the consequences of a dam failure.

Risk areas

After the DAMBREAK model is generated, a graph is created that identifies the areas at risk from the dam-break flood, in which the volume of liquid retained by the intact earthen dam is related to the maximum distance attained by the flood resulting from its breakage. With this graph it is possible to know the distance beyond which no environmental damage is to be expected. To produce this graph for our study, we obtained data about representative leachate-retaining earthen dams in Spain and took into account several necessary preliminary considerations, as follows:

- According to observations made *in situ* and inquiries made directly to the technicians at the earthen-dam installations included in our study, we determined that the average volume of liquid stored by such a dam is 75% of the maximum retaining capacity of the dam. This is a safe value because the leachate reservoirs retained by earthen dams are not typically filled to capacity, and are typically emptied when their volume surpasses 50% of capacity.
- According to the Dam Break procedure, the line of attenuation of the flow of liquid in a flood channel has its lower limit at zero as the distance reached by the flood approaches infinity. To determine a conservative value for this line, we asked 22 technicians at Spanish hydrologic institutions to provide a value for maximum flow below which a leachate flood would not produce any significant damage. The average maximum flow value was 0.10 m^3/s, and the standard deviation was 0.07 m^3/s. On the basis of these preliminary considerations, we used the following process to identify the area at risk from a leachate flood:

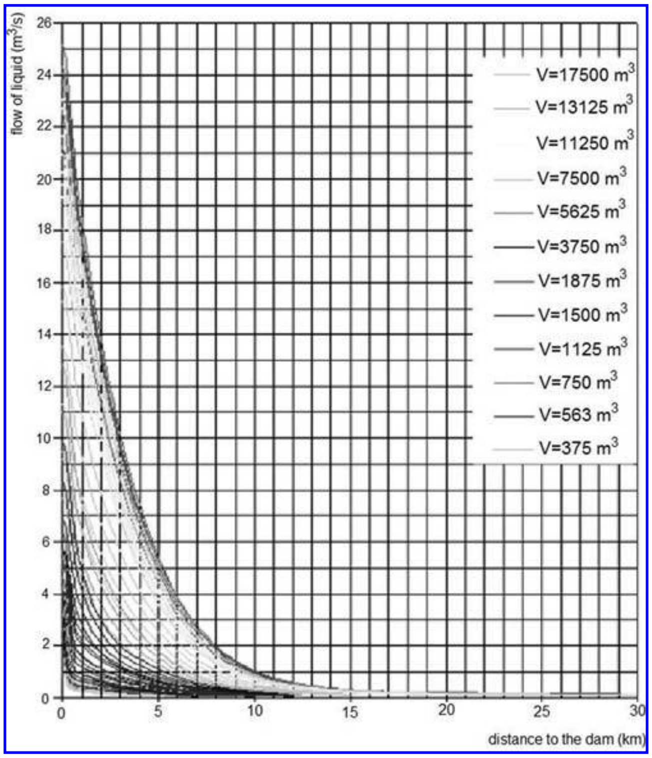

FIG. 4. Attenuation of flow of leachate vs distance.

1. We collected data from 16 known earthen dams. The data were gathered *in situ* or were provided by the earthen-dam installations that we included in the study or by their chief technicians, and consisted of the maximum capacity of the earthen dam, the top surface area of the dam, the width of the crest of the dam, the height and depth of the dam, the slope of the inner and outer embankments of the dam, and the material used to construct the dam.

2. We measured the top surfaces of 64 existing earthen dams for leachates by means of orthophotography, and from a conservative estimation of the slope of the dams' embankments as 1.5H:1V, we calculated an approximation of the height of each dam. When we compared these data with those for other known earthen dams, we found that this approach was quite acceptable.

3. Representative values for the capacity of the earthen dams were chosen as 25,000 m^3, 20,000 m^3, 15,000 m^3, 10,000 m^3, 7500 m^3, 5000 m^3, 2500 m^3, 2000 m^3, 1500 m^3, 1000 m^3, 750 m^3, and 500 m^3. This range of values includes all of the leachate dams that we observed in Spain.

4. We collected representative values for the top surfaces of the dams. This variable depends on the capacity and inner height of the dam, and is usually expressed as a proportion. The data are shown in Table 1, and include practically all of the existing earthen dams for leachates in Spain.

5. The average width of the crest of an earthen dam was taken to be 3.00 m on the basis of the observed dams. The material of which an earthen dam is made is considered to have an average degree of cohesion, and the slopes of the inner and outer embankments of the dams that we studied were taken as 33.69 degrees (1.5H:1V).

6. With the data described above, we conducted 547 runs of the simplified version of the DAMBREAK program (SMPDBRK Model; Dam Safety Office, 1992) for each case named above, with variation in the distance covered by the leachate flood in each case. This makes it possible to determine the maximum volume and flood height of escaped leachate fluid at a particular point. The result is a graph with 50 curves that relates the maximum volume of leachate fluid released by the breakage of an earthen dam to the distance from the dam at each point in the flood path (Fig. 4).

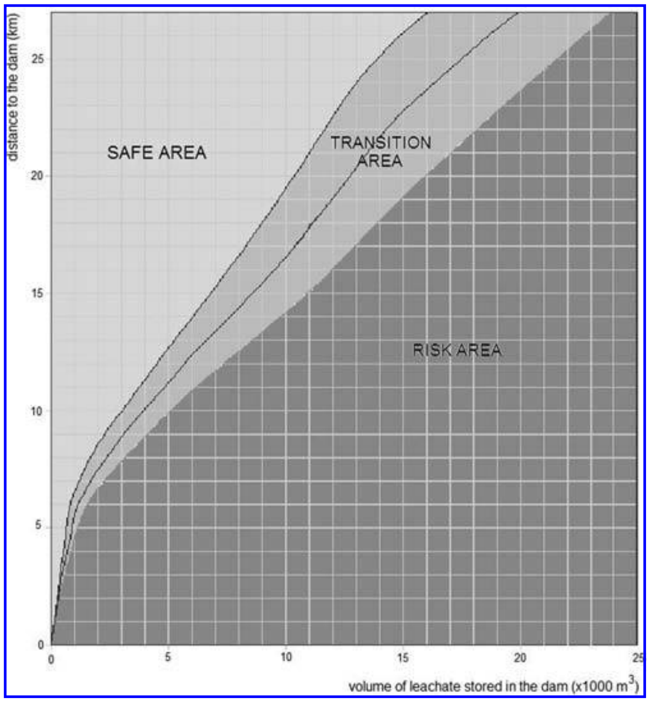

FIG. 5. Identification of safety vs distance.

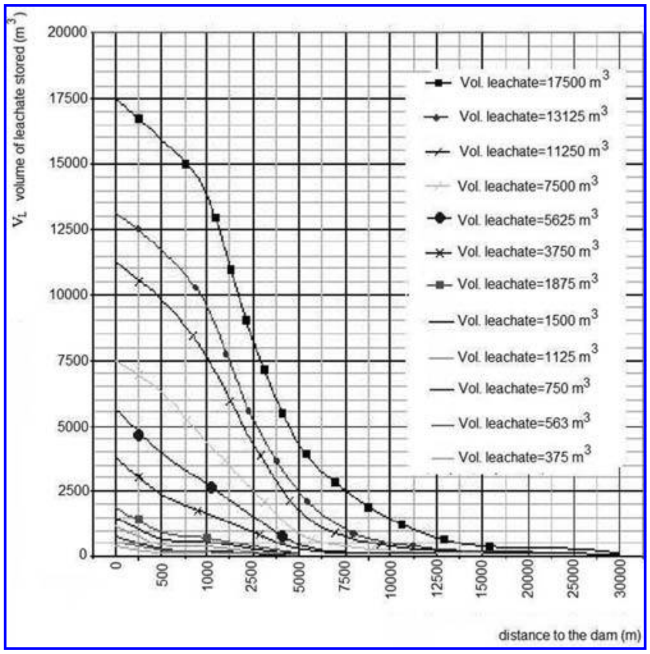

FIG. 6. Volume of leachate Vs distance.

The graph shown in Figure 5 provides the approximate maximum distance that the volume of escaped leachate would reach, or the potential risk distance. This can be influenced by a multitude of factors intrinsic to the morphology of the course of the leachate flood, and also by the conditions of the earthen dam from which the leachate fluid originates, and for this reason we added a transition zone to the graph. We also determined a safety zone consisting of the area to which an important volume of leachate is not expected to reach. This safety zone would identify the minimum distance beyond which, in case of breakage of an earthen dam, the leachate fluid would not have a significant environmental impact (Fig. 5).

Volume of leachate that reaches a given point

In order to determine the potential environmental impact of leachate released by the breakage of an earthen dam, we created a graph (Fig. 6) relating the distance covered by the leachate flood to the volume of leachate stored behind the dam (V_L). Use of this graph reveals the volume of leachate that would reach the point at which each EF is located. If, for example, a dam retains 13,000 m^3 of toxic liquid, and it is necessary to know the volume of leachate that would reach a point 1500 m downstream of the dam in the line of maximum slope below the dam, the graph in Figure 6 shows that approximately 8000 m^3 of fluid would reach this point.

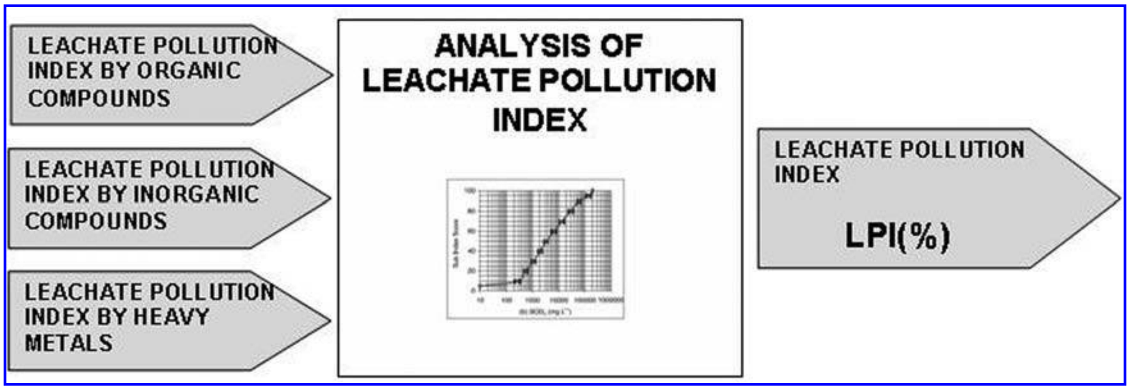

FIG. 7. Scheme to calculate LPI(%).

Polluting potency of the leachate liquid

The pollutant charge of a leachate is calculated by using the diagram shown in Figure 7. The variability in the composition of leachates makes it necessary to develop and use a leachate pollution index (LPI[%]) (Kumar and Alappat, 2005). This index establishes the pollutant charge of the leachate according to its characteristics and composition. In order to develop the index, it is necessary to analyze the leachate liquid and obtain data about its content of organic compounds (organic acids, biochemical oxygen demand [BDO], total organic carbon [COT], volatile organic carbon [VOC], etc.), inorganic compounds (chlorides, total Kjendhal nitrogen [TKN], chemical oxygen demand [COD], etc.) and heavy metals (Fe, Ni, Pb, etc.). Once these data are obtained, the method described above is applied and LPI(%) is calculated from the different rating curves for each compound.

Rating curves

The values of LPI(%) and V_L (m^3) are obtained by means of the procedure described above. As can be observed, each of these indices has its own units of measurement, which differ from one another, making the results with each index incommensurate with respect to the other.

In order to make the units used in the two indices commensurate with one another, it is necessary to use rating curves, which transform the units of each index into ERI units. In order to generate these rating curves, we asked a representative group of Spanish technicians, by means of a poll-questionnaire, to draw up the statistical correlation between the indices LPI and V_L and the ERI. The technicians were researchers and scientists working on hydrological and environmental projects. We sent out a total of 243 questionnaires, of which 93 were received in correctly completed form.

When the questionnaires had been collected, a statistical analysis was done to investigate whether the results were statistically significant and whether they could be used in the ERI EF equation. The computer program Statgraphics Plus 5.1. [StatPoint, Inc. Virginia] was used for this (Colomer, 2006), and the following linear equations were obtained:

$$\text{ERI LPI} = 0.0435897 + 0.00970667 * \text{LPI\%} \qquad (12)$$

$$\text{ERI } V_L = 0.0210256 + 0.0000472 * V_L \qquad (13)$$

The values of ERI can range from 0 to 1. The linear equations for the rating curves correspond to the ERI of the LPI (ERI LPI) and to the ERI for the volume of leachate that reaches each point on the curve of ERI V_L (Colomer, 2006).

Environmental characteristics of the medium receiving the leachate flood

The medium receiving a leachate flood can be defined as the land surface that would receive the toxic liquids released into the environment by the breakage of an earthen dam, and includes all of the EFs that this could affect either directly or indirectly.

Some leachate-retention facilities with dams are located at the heads of gullies. If the embankment of the dam breaks, the liquid stored behind the dam will spill along the line of

TABLE 2. SURVEYS SENT TO TECHNICIANS

	Received polls	*Sent polls*
Polls sent by professors at universities	49	103
Polls sent by engineers of private offices	38	57
Polls sent by civil servants from the Spanish Ministry of the Environment	27	54
Polls sent by individual engineers	10	36
Polls sent by environmental scientists	21	40
Polls sent by non-governmental organizations	33	48
Total	178	338

TABLE 3. WEIGHT OF THE ENVIRONMENTAL FACTORS

Environmental Factor (EF)	($\bar{x}_i$)	*s*	*CV*	*Weight* (w_i)
EF [1] Riverbed, channel, or water course used for human consumption.	4,92	0,27	6%	0,064
EF [2] Riverbed, channel, or water course used for agricultural consumption.	3,57	0,86	24%	0,047
EF [3] Environmental interesting place (very clean water river, lake, or stream) with presence of salmonids fish: salmon, trout, etc.	4,75	0,43	9%	0,062
EF [4] Environmental interesting place (clean water river, lake, or stream) with presence of cyprinids fish: barbs, tenches, carps, black-bass, etc.	3,93	0,78	20%	0,052
EF [5] Environmental interesting place with endemic vegetation sensitive to leachate.	4,44	0,76	17%	0,058
EF [6] Environmental interesting place with presence of bank vegetation: blackberries, reeds, willows, etc.	3,45	0,94	27%	0,045
EF [7] Very permeable soil which permit leachate to percolate towards groundwater.	4,58	0,72	16%	0,060
EF [8] Human settlement place permanent or temporal.	4,01	0,90	22%	0,053
EF [9] Recreational areas (camping, pic-nic, sportive ports, etc.)	3,32	1,11	33%	0,043
EF [10] Fish farms.	4,00	0,97	24%	0,052
EF [11] Agricultural areas with crops sensitive to leachate.	3,94	0,95	24%	0,052
EF [12] Karst areas with presence of caves and fissures.	3,55	1,01	28%	0,47
EF [13] Archaeology or historic sites.	2,96	1,18	40%	0,039
EF [14] Holes where leachate can store and affect animals.	4,07	0,91	22%	0,053
EF [15] Environmental protected areas according to Natura 2000 (National parks, natural parks, natural reservations, etc.).	4,32	1,04	24%	0,057
EF [16] Important infrastructures routes (roads, railways, electric layings, gas instillations . . .).	2,07	1,09	53%	0,027
EF [17] Forest infrastructures (paths, cattle routes, green routes, forest tracks).	2,57	1,07	42%	0,034
EF [18] Social and cultural interesting places (pilgrimage paths, sportive competitions).	2,39	1,10	46%	0,031
EF [19] Panoramic areas with visual interest.	2,72	1,22	45%	0,036
EF [20] Areas with large visibility (areas which can be observed from a town or road).	2,85	1,19	42%	0,037
EF [21] Sea water.	3,86	0,97	25%	0,051
Total ($\sum_{i=1}^{21} \bar{x}_i$)	76,26			1,000

maximum slope below the dam, which normally coincides with the course of the gully below the dam.

In order to determine the environmental impact of a flow of dangerous liquid, it is important to first know the location of each EF in the flooded area, and second to know the volume of liquid that would reach that point and whether that volume would remain there or continue its descent. The type of soil in the flooded area, and above all its permeability, is an important matter to consider, because if the leachate fluid flow reaches a karst terrain or a permeable soil, the leachate can infiltrate it, percolate through it, and pollute groundwater.

Because the medium receiving a leachate flood must be suitably studied, the EFs within the flood course that are vulnerable to toxic substances in the leachate liquid have to be identified and evaluated.

In order to identify the EFs that are of interest and are sensitive to a leachate fluid, we first followed the Delphi method. For this purpose, we sent a questionnaire to a panel of independent experts working in the fields of environmental management, monitoring, research, maintenance, and education, choosing a representative sample of experts. By means of a survey in which we sent 338 e-mails to various persons and organizations, we asked these experts to complete a list of the environmental elements that could be affected by a flood of toxic liquid. We chose an error level of 5% and 95% confidence interval (CI) for the results, and received 178 correctly completed surveys with the distribu-

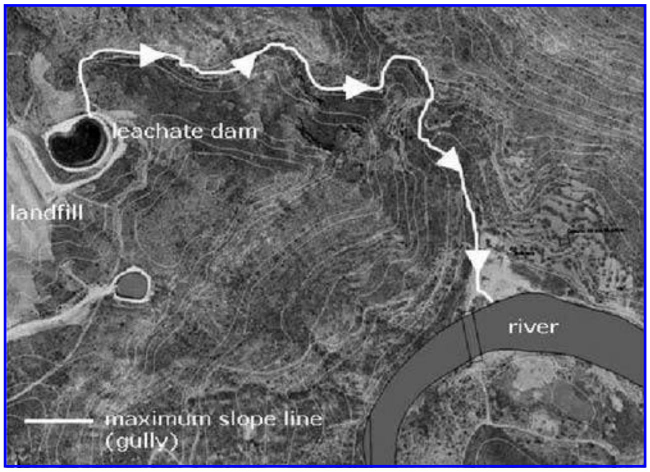

FIG. 8. Ortophotography of a leachate dam and the maximum slope line.

FIG. 9. Leachate dam for a rejects landfill.

tion of EFs shown in Table 2, which were grouped into 21 homogeneous EFs (Table 3, column 1) according to the method of Gómez Orea (2003).

Assignment of weight to EFs

According to the Delphi method, we asked the same experts, in a second questionnaire, to assess on a scale from 1–5 (ranging from least to greatest importance) the relevance of the EFs at risk of being affected by toxic liquids.

Table 3 shows the result of the analysis of the data collected in the questionnaires. As seen in the table, the value of some EFs had a very low coefficient of variance (CV), whereas others showed widely dispersed results.

To calculate the weight of each of the EFs, we determined the arithmetic sum of the mean values of importance and divided the mean value of each parameter (x_i) by the sum of all of the parameters of importance, so that:

$$w_i = \sum_{i=1}^{21} IP_i = 1 \qquad (14)$$

where

w_i = sum of weight of each EFs

IP = weighting index of each EFs

Presence of important EFs

Different EFs can be identified and values assigned to them by means of thematic maps, specialized bibliographies, and visits to the area in which they exist. If, after producing a flood map, it is observed that an EF is located within the flood zone, the potential impact of the flood on this EF can be anticipated. The sum of the EFs is then multiplied by the ERI LPI as calculated in Equation 12. On the other hand, the volume of leachate that reaches each EF is different from that reaching other EFs because the different EFs have different locations. Thus, each of the addends that make up the second factor in the formula will have to be multiplied by the ERI V_L corresponding to the coordinates of its location. The value of the volume of leachate for each point can be obtained by means of Figure 5 (Equation 13).

If a particular EF exists at a particular location, the corresponding weight will be multiplied by a value of 1. If the EF does not exist, the corresponding weight will be multiplied by a value of 0. Therefore:

$$\text{ERI EF} = \text{ERI LPI}^* \sum_{I=1}^{21} w_i \cdot EF_{[i]} \cdot \text{ERI V}_{L[i]} \qquad (15)$$

ERI EF is an index that establishes a value for the environmental risk posed by the breakage of earthen dams for leachates. The ERI EF index is a complementary tool for improving the assessment of the environmental impact and environmental risk from the breakage of leachate-retaining earthen dams, as is done in other methodologies such as the HELGA (Health and Environmental Risk Effects from Landfill Gas) model (Gregory *et al.*, 1999), the LandSim and GasSim programs (SEPA, 2002; Attenborough *et al.*, 2002; Mavropoulos, 2004), the LandGem model (U.S. EPA, 1995; U.S. EPA, 1997), and the environmental diagnostic methodology used for municipal waste landfills (Calvo *et al.*, 2001; Calvo *et al.*, 2005; Calvo *et al.*, 2006).

Applications

In order to validate the methodology described in this paper, we applied it in nine cases (Table 4). The cases involved nine earthen dams for leachates, including dams retaining landfill reject material (3 cases), non-hazardous waste landfill (1 case), leachates from composting plants (2 cases), municipal solid waste (2 cases), and toxic waste (1 case). The re-

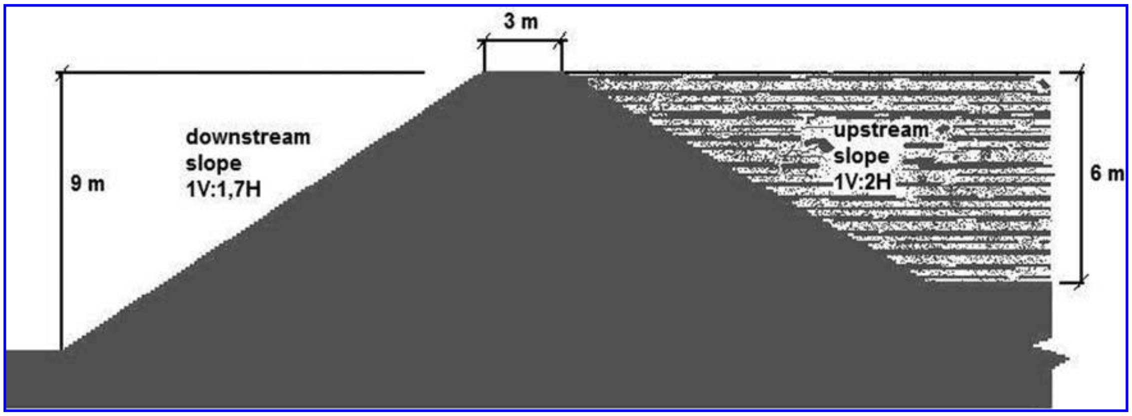

FIG. 10. Scheme of a leachate dam: cross-section.

Table 4. ERI EF for Different Leachate Dams

Case	*Leachate earth dam*	*Capacity of the dam (m^3)*	*ERI EF*
Case 2	Rejects landfill [1]	13600	0.048
Case 3	Compost plant [1]	2200	0.044
Case 4	Nontoxic wastes landfill [1]	14000	0.028
Case 5	MSW landfill [1]	27000	0.064
Case 6	MSW landfill [2]	10000	0.019
Case 7	Compost plant [1]	25000	0.028
Case 8	Toxic wastes landfill	15000	0.118
Case 9	Rejects landfill [2]	9000	0.071

sults for the ERI EF indices for the nine dams are shown in Table 4; however, we did an exhaustive analysis of Case 1, involving an earthen dam for leachate from rejected landfill material, to illustrate use of the methodology described here.

Case 1: Earthen dam for leachate from rejected landfill material

In the case of breakage of an earthen dam for retaining leachate liquid, the volume of liquid that reaches each EF downstream of the dam will depend on its distance from the dam, with the polluting power of the leachate liquid being considered invariant.

Case 1 involves an earthen dam retaining leachate generated from rejected landfill material. The dam that retains the landfill leachate is located at the head of a gully in a natural area with Mediterranean fauna and vegetation, some components of which are environmentally protected. The type of soil downstream of the dam is nonpermeable, but some caves and cracks have been found in the surrounding area. Ruins of an old water mill are present in the flow-bed of the gully. The gully has an irregular path with considerable vegetation, cobblestones, and even small pine trees. The gully empties into a river that has clean water and is a typical location for trout-fishing, with a fish farm located downstream of the gully entry point.

The breakage of the earthen dam would release a cascade of leachate that would advance along the natural channel of the gully until it reached the river (Fig. 8).

Characteristics of the earthen dam The earthen dam in the case described here (Case 1) can retain 14,000 m^3 of liquid. The characteristics of the dam are shown in Figures 9 and 10 and Table 5. These data are needed for application of the Dam Break methodology and to identify the areas at risk from breakage of the dam.

Leachate pollution charge Average data for the leachate retained by the earthen dam, obtained from periodic analyses, are given in Table 6. According to the methodology of Kumar and Alappat (2005), the LPI(%) = 29.386%. Using this value in Equation 12 yields:

$$\text{ERI LPI} = 0.0435897 + 0.00970667 \cdot \text{LPI} = 0.329 \quad (16)$$

Characteristics of the environment To determine the environmental effect of breakage of the earthen dam being discussed here, it is necessary to identify the presence or absence of each EF in the area downstream of the dam, and its distance from the dam. If a specific EF is present in the flood area, it is assigned a value of 1 ($EF_{[i]}$ =1), and if not present it is given a value of 0. Table 7 shows the data needed to calculate the ERI EF.

As an example of the use of the flood-damage identification process, EFs for the area that would be flooded in Case 1 are shown in Table 7. In this example, the ERI V_L corresponding to $EF_{[3]}$ is determined, The river described earlier is 2050 m downstream from the earthen dam, and the average of maximum volume of leachate retained by the dam is 14,000*0.75 = 10,500 m^3. Therefore, according Figure 5, the volume of leachate that would reach the river is approximately 6500 m^3. This value, inserted in Equation 13, provides an ERI V_L $EF_{[3]}$ = 0.328.

The values of ERI V_L for other environmental factors are calculated in the same way as shown for $EF_{[3]}$. With the values calculated for each EF, Equation 15 can be used to obtain the value of the ERI of the identified EFs, as follows:

$$\text{ERI EF} = 0.042 \quad (17)$$

Other cases

We have applied the same methodology described here to eight other cases of Spanish earthen dams for leachates. The ERI EF values for these are shown in Table 7. These earthen dams are considered safe installations because they have had no accidents during their operational lives. On the basis of the data obtained from this work, we can advise, although

Table 5. Characteristics of the earth dam: case 1

Height of the slope downstream	9 m
Depth	6 m
Capacity	14000 m^3
Width of the crest	3 m
Slope downstream of the embankment	30° (1V:1.7H)
Slope upstream of the embankment	26.6° (1V:2H)
Material of the dam	Well graduated material with good mechanical properties

Table 6. Average analysis of leachate, case 1

Contaminant	*Quantity (mg/l)*
BOD_5	5433
COD	22360
pH	7.7
$[Cl^-]$	2543
TKN	363
$[NH_4^+]$	511
Total solids	16850
[Cr]	1.8
[Pb]	4.05
[Cu]	0.61
[Hg]	0.04
[Fe]	289
[Ni]	0.73

only as a guideline value, an ERI EF < 0.150–0.200 as the highest permissible limit for earthen dams for leachate. It would be necessary to obtain more ERI EF data, for different earthen dams used for retaining toxic liquids, to establish an accepted universally safe value of ERI EF.

In any case, the environmental authorities responsible for the area around an earthen dam that is used for retaining leachate fluid must consider the environmental risk posed by the facility in deciding to accept or overrule its construction.

Conclusions

The methodology that we have described for assessing the potential impact on the environment of the breakage of an earthen dam for retaining toxic leachate liquid was devel-

Table 7. Calculation of ERI VL for Each EF

Environmental Factor (EF)	*Presence/ absence EF [i]*	*Distance from de dam to the EF (m)*	*V_L Maximum volume of liquid which can reach the EF (m^3)*	*ERI V_L in that point*	*Weight of the EF w_i*
EF [1] Riverbed, channel, or water course used for human consumption.	0				
EF [2] Riverbed, channel, or water course used for agricultural consumption.	0				
EF [3] Environmental interesting place (with very clean water river, lake, or stream) with presence of salmonids fish: salmon, trout, etc.	1	2050	6500	0,328	0,060
EF [4] Environmental interesting place (with clean water river, lake, or stream) with presence of cyprinid fish: barbs, tench, carps, black-bass, etc.	0				
EF [5] Place of environmental interest with endemic vegetation sensitive to leachate.	1	700	10200	0,502	0,057
EF [6] Place of environmental interest with presence of riparian communities on the banks: blackberries, reeds, willows, etc.	0				
EF [7] Very permeable soil which allows leachate to percolate towards groundwater.	0				
EF [8] Places with permanent or seasonal human settlement.	0				
EF [9] Recreational areas (camping, picnic, leisure harbors, etc.)	0				
EF [10] Fish farms.	1	2250	6000	0,304	0,052
EF [11] Agricultural areas with crops sensitive to leachate.	0				
EF [12] Karst areas with presence of caves and fissures.	1	1950	6500	0,328	0,047
EF [13] Archaeological or historical sites.	1	1450	8500	0,422	0,047
EF [14] Holes where leachate can accumulate and affect animal life.	1	1750	7500	0,375	0,045
EF [15] Environmentally protected areas according to Natura 2000 (National parks, natural parks, natural reserves, etc.).	0				
EF [16] Important infrastructures routes (roads, railways, electric power lines, gas instillations, etc.).	0				
EF [17] Forest infrastructures (paths, cattle routes, greenways, forest tracks).	0				
EF [18] Places of social and cultural interest (pilgrims' ways, sports competitions).	0				
EF [19] Panoramic viewpoints.	1	1800	7000	0,351	0,034
EF [20] High visibility areas (areas which can be observed from a town or road).	0				
EF [21] Sea water.	0				

oped as an alternative to existing general models for evaluating the environmental risk from such an event. After creating and applying this methodology to real cases involving such dams, we reached the following conclusions:

- The environmental risk generated by breakage of an earthen dam consists fundamentally in possible seepage of liquid and/or the possibility of the embankment of the dam breaking with spillage into the surrounding area of the liquid being retained behind the dam.
- The methodology for determining the ERI based on EFs is founded on information about and exhaustive analysis of the characteristics of the earthen dam, the characteristics of the cataract released by breakage of the dam, and the characteristics of the environment in which the dam is located.
- In order to evaluate the environmental impact of the breakage of such a dam, it is necessary to analyze the flood resulting from such breakage, to consider the volume of liquid stored behind the dam at the moment of the breakage, and to know the polluting potency of this liquid.
- In its simplified version, the DAMBREAK methodology provides data about the maximum discharge flow and the flood path resulting from breakage of a leachate-retaining earthen dam, permitting creation of a flood map. By calculating the flow, volume, and depth of the leachate flood, the DAMBREAK methodology also allows determination of whether an EF located at a certain distance from a broken earthen dam will be affected by the resulting leachate flood.
- Once the flood map is known, it is necessary to make a detailed study of the affected area. This is accomplished by creating an inventory of the important EFs that could be affected by the leachate. The panel of experts used in our study assigned a weight to each of various EFs.
- All of the data collected for the DAMBREAK methodology have their own specific units of measurement. In order to be able to operate with them, their units have to be made mutually homogenous, so that the data they represent become units of environmental risk whose values will fall within the interval 0–1.
- The application of this methodology to real cases has been validated, in that the values we obtained in nine cases of earthen dams for leachates were very low. In fact, these nine earthen dams can be considered as safe facilities in having had no accidents in the years that they have been in operation.

The main utility of ERI EF is its application to cases of leachate-retaining earthen dams in their design phase. If its ERI EF is reduced prior to the construction of an earthen dam for leachate, the dam can be made safer and its probability of damage to the environment in case of its rupture will be lower. We believe that the environmental authorities responsible for a particular dam must establish a safe value for the ERI EF of the dam, so that permission to create the dam will be granted if its ERI EF is below this safe value.

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