HUMAN HEALTH RISK ASSESSMENT OF LEACHATE LEAKAGE FROM A SOLID WASTE LANDFILL

Magni[1], A., Massabò[1] M. e Paladino[1,2], O.
[1] CIMA Research Foundation - International Centre on Environmental Monitoring, University Campus – via A. Magliotto 2, Savona, 17100, Italy
[2] DIST – Department of Communication Computer and System Sciences, University of Genova, Via Opera Pia 13, Genova, 16145, Italy

SUMMARY

Human health and water resources risk assessment of a confined Municipal Solid Waste (MSW) landfill, settled in Liguria, Italy has been performed. The risk assessment for human health, groundwater and surface water is quantified for different scenarios. Transport of pollutant is simulated by means of the Multimedia Environmental Pollutant Assessment System (MEPAS), while leachate loss from the bottom of the landfill is evaluated by solving the water balance through the software HELP 3 (Hydrological Evaluation of Landfill Performances). Risk of groundwater, surface water and human health are compared with the maximum acceptable levels. Risk for groundwater in well above the limits for all scenarios here analyzed. Risk for river and human health are much below the acceptability limits. The most important human exposure pathways is ingestion of fish and dermal contact with contaminated water for carcinogenic chemicals, while teh ingestion of contaminated vegetables are more important for non-carcinogenic compounds. The scenario of operating landfill is compared with the postclosure case, resulting in a higher risk of the former.

1 INTRODUCTION

A landfill is a facilty where waste are collected in cells and are subjected to natural processes of degradation. The most concerning emissions, resulting from waste degradation are biogas and leachate, but while there are evidence that biogas is sufficiently oxidised after 10-15 years and does not have significantly impact on the environment, the leachate toxicity can last for a longer period.

Leachate is a liquid that it is collected at the bottom of the landfill and it is the result of the percolation of precipitation, water initially contained into the waste, irrigation and infiltrating water into the landfill. Leachate contains a variety of chemical consituents derived from the solubilization of the materials deposited into the landfill and from the products of chemical and biochemical reactions occurring within the landfill. The chemical composition of leachate can vary from cell to cell within the same landfill, depending from the degradation state of wastes. Many studies about leachate toxicity for human health have been made during the last years, demonstrating the existence of relations between the exposition to chemicals of human population and the occurence of many pathologies. In particular, Vrijheid [1], the Health Research Board [2] and the Civil Protection of Campania [3] found, betwen human populations analysed, relations between exposition to leachate chemicals and adverse effect to both human health and ecological system.

Risk assessment is a tool continuously developed and applied to different fields: from food industry to economic etc etc.. Several risk assessment tools are present in the literature, however no one of them has a quantitative and integrated methodology for carrying out risk assessment specifically for landfill leachate (see Butt et al. [4]). The risk assessment is a most important factor of an effective risk control, as the degree of success of the latter is based on the former. Thus, the degree of effectiveness of the risk control or reduction is highly depended on the information derived from the risk analysis.

The aim of the present work is to show how risk assessment can be used for evaluation of environmental impacts of new and existing landfill sites, identify the most important exposure pathways and chemicals of concerns, plan prevention and remediation strategies.

The work is presented as following. Source characterization, models used for pollutant transport and risk characterization are presented in the section of Methods, while the results for a landfill site located in the Liguria region are presented in the section Results. Conclusions are finally delineated.

2 METHODS

The risk assessment has been applied to a confined Municipal Solid Waste (MSW) landfill, settled in the Liguria Region, Italy. The total volume of waste disposed into the landfill is about 250 m^3 for a covered area of about 50 m^2. The landfill is located next to a surface water body in connection with a tin aquifer that flows from the landfill towards the river. The river is used as recreational site and for other human activities such fishing and intensive irrigation of croplands.

Confined landfills usually include a cover system that reduce water infiltration into the wastes, a sealing system to prevent the movement of leachate to groundwater and a leachate and biogas collection system. Emission from a MSW landfill are biogas and leachate, however, there are evidence that biogas is sufficiently oxidised after 10-15 years and does not significantly impact on the environment, while leachate toxicity can last for a longer period of time.

The landfill has a liner system composed by a drainage layer and an artificial system that includes a geomembrane and a soil layer with low hydraulic permeability. Studies about geomembranes quality have shown that even the better ones are often affected by flaws, due to both manufacture and installation of the liner. Leakage through the geomebranes of the leachate produced into the landfill can’t be totally avoided. The highest the density of flaws (number per unit area), the most is the leachate infiltrating into the subsoil beneath the geomembrane.

The human health risk is highly affected by both the rate loss of leachate form the liner system and chemicals concentration. In order to assess the risk, four different scenarios are considered. It follows a brief description of the four configurations and their influence upon leachate production and leakage.

- Scenary 1. Operating landfill and properly working sealing system;
- Scenary 2. Operating landfill and failure of the sealing system. In this case the performance of the landfill has been evaluated with the break of geomembrane; the leachate loss rate significantly increases;
- Scenary 3. Postclosure landfill and properly working sealing system. In this case the landfill is covered and the water infiltration into the wastes is minimized, no leachate recirculation is active;
- Scenary 4. Postclosure landfill and failure of the sealing system. In this case has been evaluated the residual leachate leakage through the failed geomembrane after the closure of the landfill and its cover.

2.1 Source Characterization

The first step of the risk assessment was the characterisation of the primary source of pollution: the leachate. The characterisation has followed two steps: the quantification of leachate losses (*L*) from the bottom of the landfill and the pollutant concentrations itself (C_i). The mass flux (F_i) of the *i*-th pollutant through the landfill liner system is estimated by $F_i=L\ C_i$..

The leachate rates loss *L* is estimated by solving the hydrological balance of the landfill. The hydrological balance of the landfill has been obtained through the application of the software HELP 3 (Hydrological Evaluation of Landfill Performances [5]) on a daily basis for a time horizon of 30 years. Figure 1 show the water balance, as it is solved by HELP, in wich six terms are considered: precipitation, evapo-transpiration, runoff, actual infiltration, leachate recirculation and leachate loss (leakage).

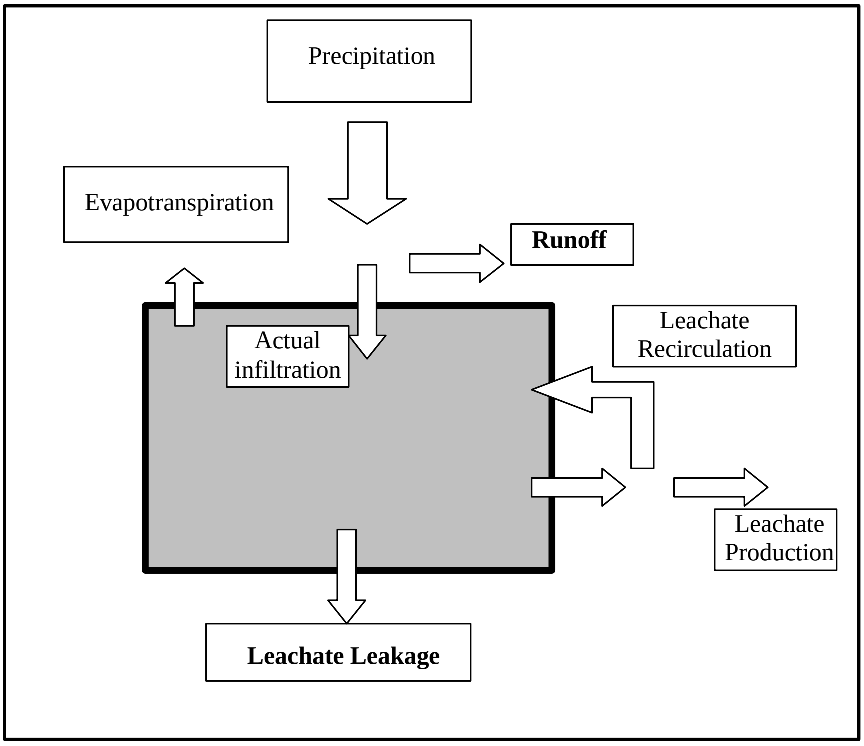

Figure 1. Landfill Hydrological balance as solved by HELP 3 (Hydrological Evaluation of Landfill Performances).

The input data, needed in order to solve the landfill water budget, are basically meteorological and landfill design data. The software HELP 3 needs four categories of meteorological datas: daily precipitation height (mm); daily air temperature (°C); daily solar radiation (MJ/m^2); data for the estimation of the evapotranpiration, such as average annual wind speed at ground, relative air moisture, site latitude.

The meteorological data have been synthetically generated based on the 30 years historical record. A sample of 30 years of meteorological data from 1976 to 2006 has been used. The daily values of precipitation for each year have been simulated through a statistical model. The statistical model simulates the rainfall as a Poisson Rectangular Pulses stochastic process. The statistical parameters of the Poisson process are obtained from the analysis of a 30 years of hystorical series of meteorological data at the site. Details of the approach can be found in Magni [6].

The daily values of solar radiation were simulated on the basis of the astronomic radiation, of the daily cloud cover of the sky and of the latitude of the site. The daily cloud cover of the sky has been set to be equal to 0.95 for cear sky, 0.65 for shallow clouds, 0.5 for covered sky and 0.15 for very covered sky. The air temperature, wind speed at ground and relative air moisture were obtained as averaged values over 30 years records.

The leachate composition is highly variable in time and uncertain. No site specific data were available for the leachate composition of the considered landfill. Data of the chemical composition of the leachate has been taken by the literature, considering in particular 10 pollutants, between the most commonly present in typical MSW landfill, Benzene, Toluene, Xylene, Ammonia, Lead (Pb), Nickel (Ni), Metyl-butil-etere (MTBE), Trichloroetylene(TCE), Naphtalene, Etylbenzene. Typical concentrations are reported in Table 1.

Table 1. Observed concentration ranges for the considered contaminants, in common MSW leachates

	Benzene	**Toluene**	**Xylene**	**Ammonia**	**Pb**
C_{min} (mg/l)	0.001	0.001	0.004	30	-
C_{avg} (mg/l)	0.8	6	1.7	740	0.065
C_{max}(mg/l)	1.63	12.3	3.5	1450	0.15

	Ni	**MTBE**	**TCE**	**Naphtalene**	**Etyl-benzene**
C_{min} (mg/l)	-	-	0.0007	0.0001	0.0001
C_{avg} (mg/l)	0.17	0.017	0.375	0.13	0.64
C_{max}(mg/l)	0.3	0.035	0.75	0.26	1.28

2.2 Multimedia Transport Models and Exposure Assessment

Mathematical models with different degree of complexity can be used to describe the transport of pollutant in the environment and the food chain. These models aim at estimate the exposure concentration taking into account attenuation process such as dilution, dispersion, volatilization, biotic and abiotic degradation, bioaccumulation, etc. A schematic of the conceptual model of exposure pathways for human receptors is described in Figure 2.

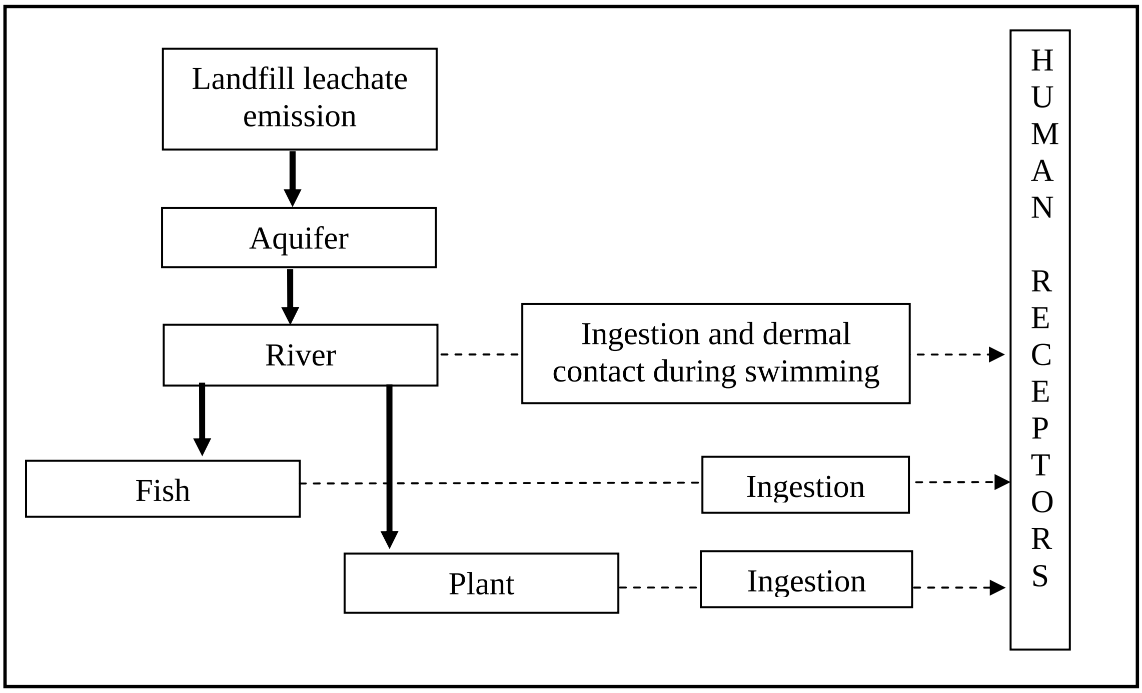

Figure 2. Conceptual model of the exposure pathways for human receptors.

The risk assessment has been performed with the aid of the software Adaptive Risk Assessment Modeling System (ARAMS) [7], where every section of the conceptual model of the site is described by a different module. The fate and transport of pollutant is solved by the Multimedia Environmental Pollutant Assessment System (MEPAS) [8]. Every module were analysed by a model, in this case MEPAS. After the characterisation of the source of contamination, the contaminant transport dynamics into the vadose zone and the aquifer were neglected, because of the neglecting dimensions of the two areas. In this way the whole fluxes of leachate coming out from the landfill were supposed to enter the river by a groundwater pathway, supplying transient contaminant fluxes along the stream bank adjacent to the aquifer.

Transport of chemicals into the river has been modeled by the surface-water component of MEPAS. This model provides estimates of contaminant concentrations in a river at locations downstream from a release point. Because contaminant releases to a river in the MEPAS methodology are generally of long duration relative to the travel time from the point of release to a receptor, the migration and fate of contaminants through the river pathway are described by the steady-state, two-dimensional advective-dispersive equation for solute transport. The surface-water equation accounts for the major mechanisms of constituent persistence (i.e., degradation/decay), advection, and hydrodynamic dispersion. Persistence is described by a first-order degradation/decay coefficient. Advection is described by constant unidirectional flow in the longitudinal direction. Hydrodynamic dispersion is accounted for in the lateral direction. The processes associated with adsorption/desorption between the water column and suspended and bed sediments are not addressed, however, neglecting these processes should, in most cases, represent a conservative assumption with regard to water column contaminant concentrations.

The exposure pathway component of the Multimedia Environmental Pollutant Assessment System (MEPAS) provides an estimate of exposure to selected individuals and population. Human beings are exposed to chemical through the river, by ingestion of fish living in the contaminated river, by ingestion of vegetables irrigated with river water, accidental ingestion and dermal contact during swimming in the contaminated river. The exposure pathway analysis starts with pollutant concentration in a transport medium and estimates the Lifetime Average Daily Dose (LADD [mg/kg/d], the average daily intake rate of chemicals) to exposed individuals from contact with the transport medium or a secondary medium contaminated by the transport medium. Each exposure pathway analysis in MEPAS involves definition of a transport medium (or medium of measurement), an exposure route for transfer of pollutant from the transport medium to man and exposure conditions for the individual receiving the pollutant. The pollutant concentration in the transport medium is the starting point for the exposure and health impact analysis. This concentration is generally represented within MEPAS as a 70-year averaged value. When the exposure duration is less than 70 years, the concentration represents the average for the exposure duration considered for a given exposure scenario.

In this case for agricultural and fishing pathways, models were used to estimate the transfer of pollutants from the irrigation or fishing water to the food consumed by humans. The average daily dose of a pollutant for an exposure pathway involves consideration of the rate of intake (ingestion, dermal absorption, inhalation, or external radiation dose), the frequency of exposure, the exposure duration, the averaging time, and the body weight of the exposed individual or an average member of the population. Health impact models are used to estimate the health impacts from exposure to the pollutant of concern. Models are defined for noncarcinogenic chemicals and carcinogenic chemicals.

2.3 Risk Characterization

The risk assessment is defined as a systematic process for the estimation of every risk factor in an exposition configuration, affected by hazards. The health risk assessment in particular focuses on adverse effects on human health and considers an Hazard, for toxic chemicals and a Risk, for carcinogenic chemicals. The HAZARD is evaluated with an Hazard Index (*HI*):

$$HI = LADD / RfD \quad [-], \tag{1}$$

where, LADD= chemical Lifetime Average Daily Dose (mg/Kg/d) as computed by MEPAS module and RfD is the reference dose, which represent the threshold value underneath which there are no observed adverse effects for human health. The cancer risk (*CR*) is quantified through the relation:

$$CR = LADD \cdot SF \quad [-], \tag{2}$$

where *SF* is the Slope Factor that represents the excess risk for unity dose, $(mg/Kg/d)^{-1}$. If *CR* is less than 10^{-6} the cancer risk is acceptable [9].

In order to account for the pollution of water resources, two different indexes has been introduced [10]. The risk has been quantified in terms of Hazard Quotient (*HQ*), quotient between the average chemicals concentrations calculated into the aquifer (C_{GW}) or in the river (C_R) and the threshold limit for groundwater (C_{GW-law}) or surface water (C_{R-law}) (D. Lgs 152/2006):

$$HQ_{GW} = C_{GW} / C_{GW-law} \ , \tag{3}$$

$$HQ_R = C_R / C_{R-law} \ , \tag{4}$$

HI, *CR*, HQ_{GW} and HQ_R can be computed for a general chemicals "i" and "exposure pathways "j", resulting in the definition of the following cumulated indexes which allows to identify either the exposure pathway or chemical of major concern. Concerning the exposure pathways, the following relative indexes can be defined:

$$HI_j = \sum_i HI_{ij} \Big/ \sum_i \sum_j HI_{ij} \qquad CR_j = \sum_i CR_{ij} \Big/ \sum_i \sum_j CR_{ij} \ , \tag{5}$$

$$(HQ_{GW})_j = \sum_i (HQ_{GW})_{ij} \Big/ \sum_i \sum_j (HQ_{GW})_{ij} \qquad (HQ_R)_j = \sum_i (HQ_R)_{ij} \Big/ \sum_i \sum_j (HQ_R)_{ij} \ , \tag{6}$$

Higher values of HI_j, CR_j, $(HQ_{GW})_j$ and $(HQ_R)_j$ identify the most important exposure pathway, thus risk mitigation measures that "break" those exposure pathways are the most effective in decreasing the human health risk and increasing water resources preservation. Analogously the most dangerous chemicals can be identified by using the following relative indexes:

$$HI_i = \sum_j HI_{ij} \Big/ \sum_i \sum_j HI_{ij} \qquad CR_i = \sum_j CR_{ij} \Big/ \sum_i \sum_j CR_{ij} \ , \tag{7}$$

$$(HQ_{GW})_i = \sum_j (HQ_{GW})_{ij} \Big/ \sum_i \sum_j (HQ_{GW})_{ij} \qquad (HQ_R)_i = \sum_j (HQ_R)_{ij} \Big/ \sum_i \sum_j (HQ_R)_{ij} \ , \tag{8}$$

Site indexes are useful in order to compare the different scenarios here analyzed. *HI*, *CR*, HQ_{GW}, HQ_R of the site (here and after *site-HI*, *site-CR*, *site-*HQ_{GW} and *site-*HQ_R) are intended as the summation over all the chemicals and pathways (i.e, $site-HQ_{GW} = \sum_i \sum_j (HQ_{GW})_{ij}$; the other indexes are equivalently evaluated).

3. RESULTS

The results of the simulations performed by HELP 3 are synthetically summarized in Table 2. HELP 3 estimates the leachate production and leachate leakage from the bottom of the landfill. The leachate leakage flux though the bottom of the landfill dramatically increases if the liner fails (98-99 % of the produced leachate). With a properly working liner system the leakage is roughly 2-3% of the leachate production.

Table 2. Leachate production and leakage rate as simulated by HELP 3. Results are mean values over a year.

Landfill scenary	***Leachate production [m³/y]***	***Leachate leakage - L [m³/y]***	***Leachate leakage [%]***
1-Operating landfill with intact liner	3424	73	2
2-Operating landfill with liner failure	2428	2387	98
3-Postclosure landfill with intact liner	105	4	2.5
4-Postclosure landfill with liner failure	96	95	99

The leachate leakage is the source of contamination. The mass flux (Fi) of the i-th pollutant through the landfill liner system can be estimated by multiplying the leachate leakage L by the pollutant concentration of Table 1. The risk assessment is here performed by using maxim values of pollutants concentrations of Table 1.

3.1 Groundwtaer and river risk assessment

Table 3 shows the results of the *site-*HQ_{GW} and *site-*HQ_R.The risk is reported for all the configurations analyzed. In every situation the values of *site-*HQ_{GW} are remarkably much larger than 1 (which is the maximum acceptable level of hazard quotient), indicating that groundwater resources are depleted and an unacceptable risk press on for the aquifer. In spite of the large *site-*$HQ_{GW,}$ *site-*HQ_R has been found considerably under the safety threshold. The main reason of such small *site-*HQ_R is that the river concentration is quite small because of dilution, mixing and degradation that occur along the stream flow.

Table 3. Results for *site-*HQ_{GW} and *site-*HQ_R for all the scenarios analyzed

Landfill scenary	***site-*HQ_{GW}**	***site-*HQ_R**
1-Operating landfill with intact liner	1503	2.24×10^{-4}
2-Operating landfill with liner failure	49364	1.35×10^{-3}
3-Postclosure landfill with intact liner	75	9.53×10^{-6}
4-Postclosure landfill with liner failure	1973	4.18×10^{-4}

The highest *site-*HQ_{GW} (about 50000) is found for the scenario of operating landfill and liner failure, while the presence of an intact liner decreases the site-hazard quotient for groundwater by a factor of 30. The postclosure care of the landfill present a much smaller risk for both intact and failed liner system, even though the risk is always above the acceptability criteria for both cases. In this case the landfill is covered and the water infiltration into the wastes is minimized. The presence of an intact liner decreases the *site-*HQ_{GW} by a factor of about 25, which is quite similar to what has been found for the operating landfill case.

For each single chemical the values of HQ allowed to retrace the ones exceeding the threshold limits for groundwater. This is an important information to plan intervention and remediation strategies. For every anaysed configuration, MTBE resulted the most concerning contaminant, followed by Benzene, TCE and Lead.

3.2 Human Health risk assessment

The first step to quantify the risk for human health was the exposure computation, that gives information about the quantities of contaminants that can be assumed by the receptors for every unit mass (kg) of volume (l) of food/water ingested, depending by the exposure pathway. The second step for the human risk assessment is the evaluation of chemicals doses assumed by the receptors. The dose represents the quantity of chemicals assumed by the receptors for kg of body weight and day through its life (*LADD*).

The results obtained for the MEPAS model show that lead, etylbenzene, naphtalene, nikel, toluene, xylene are accumulated in fish while the most important chemicals accumulated in the vegetables are: benzene, MTBE, amonia and TCE. Moreover, concerning the *LADD*, the results highlighted the followings: the highest doses (*LADDs*) for ingestion of vegetables are found for benzene, MTBE and ammonia; the highest *LADDs* for ingestion of fish are found for ethylbenzene, lead, naphtalene, nikel, toluene, TCE, xylene; the highest *LADDs* for ingestion of water are found for MTBE, nikel, ammonia, lead; the highest *LADD*s for dermal contact with contaminated water are found for benzene, etylbenzene, naphtalene, toluene, TCE, xylene.

Table 4 shows the results for the *site-HI* and *site-CR*, obtained from the sum over all the chemicals and the pathways. The threshold acceptability limits is 1 for *site-HI* while 10^{-6} for *site-CR*. It is possible to observe that for both carcinogenic and non-carcinogenic risk the values are acceptable and the site should not pose any relevant risk to human health. However some remarkable differences are evident among the scenarios.

Table 4. Results for *site-HI* and *site-CR* for all the scenarios analyzed

Landfill scenario	***site-HI***	***site-CR***
1-Operating landfill with intact liner	$7.7\ 10^{-5}$	$3.18\ 10^{-10}$
2-Operating landfill with liner failure	$2.5\ 10^{-3}$	$1.04\ 10^{-8}$
3-Postclosure landfill with intact liner	$3.9\ 10^{-6}$	$1.6\ 10^{-11}$
4-Postclosure landfill with liner failure	$1.02\ 10^{-4}$	$4.2\ 10^{-10}$

Site-HI and *site-CR* are very low for the scenario of postclosure landfill care and intact liner. The main reasons is that the landfill cover works as a barrier to the infiltration of rain water into the landfill, resulting in a smaller amount of leachate production. Moreover, since the liner is still intact the leachate leakages are minimal. If during the landfill postclosure the sealing system fails, both the non-carcinogenic and carcinogenic risk should increases by a factor of about 25, which is related essentially with the increased contaminant flux through the bottom of the landfill. When the landfill is operating the leakages are larger, resulting in a non-carcinogenic and carcinogenic risk which is larger, by a factor of 20 to 25, than the risk obtained in the postclosure scenarios. The rupture of the liner system will cause and increment of the risk by a factor of about 30 for both *site-HQ* and *site-CR*.

Table 5 and Table 6 show respectively the results of the relative Hazard Index (HQ_j *or* HQ_i) and Cancer Risk (CR_j *or* CR_i) of the pathway "j"and of the chemical i, computed through Equation (5) and equation (7), for the second scenario (Operating landfill with liner failure). Though similar results are obtained for the other scenarios, the case of liner failure is of special interest. Indeed in order to plan emergency interventions and remediation strategies, the relative HQ_j, CR_j are essential for the identification of the exposure pathways and the chemicals that lead to the biggest impact on human receptors.

The results obtained and reported on Table 5 show that the pathway of major concern for carcinogenic risk is fish ingestion, which account for the 70% of the total risk followed by dermal contact with contaminated water during swimming (23.5%). The remaining pathways account for less than 7% of the total risk. Concerning the non-carcinogenic risk the vegetable ingestion produce more than 96% of the site risk while less than 4% is for fish and water ingestion and dermal contact. These results suggest that an emergency plan should be oriented to the temporary suspension of ingestion of fish and vegetables coming from the surrounding area of the landfill. Note that, since no livestock breeding are present near the site, ingestion of contaminated food like meat or milk is not important.

Table 5: Hazard Index and Cancer Risk for each exposure pathway. The results are relative to the second scenario (Operating landfill with liner failure).

	Fish Ingestion	**Water Ingestion**	**Dermal contact**	**Leafy Vegetables Ingestion**	**Other vegetables ingestion**
$HI_j = \frac{\sum_i HI_{ij}}{\sum_i \sum_j HI_{ij}}$ [%]	4.00	0.34	0.29	40.40	56.40
$CR_j = \frac{\sum_i CR_{ij}}{\sum_i \sum_j CR_{ij}}$ [%]	70.20	1.69	23.5	3.10	1.93

The results obtained and reported on Table 6 show that the chemical of major concern is toluene for carcinogenic risk, which account for the 91% of the total risk. The remaining chemicals account for less than 9% of the total risk. About the non-carcinogenic pollutants, the ammonia produces more than 99% of the site risk, while the other chemicals give a negligible contribution. These results suggest that in case of accident, the remediation and emergency plans should be oriented to techniques able to attenuate ammonia and toluene concentrations.

Table65: Hazard Index and Cancer Risk for each chemicals considered. The results are relative to the second scenario (Operating landfill with liner failure)

	$HI_j = \frac{\sum_i HI_{ij}}{\sum_i \sum_j HI_{ij}}$ [%]	$CR_j = \frac{\sum_i CR_{ij}}{\sum_i \sum_j CR_{ij}}$ [%]
Benzene	0.035	0.6
Etylbenzene	0.09	-
Lead	0.44	-
MTBE	0.0001	-
Naphtalene	0.014	-
Ammonia	99	-
Nickel	0.2	8.4
Toluene	0.02	91
TCE	0.007	0.05
Xylene	0.04	-

4. CONCLUSIONS

The risk assessment approach allows to compare the operating and postclosure landfill with properly working liner system with the case of sealing failure on the base of the effects upon human health. Moreover, the approach permits to identify the most risky chemicals and subsequently drive a monitoring strategy.

The human health risk is highly affected by both the rate loss of leachate form the liner system and chemicals concentration. In order to assess the risk on receptors represented by human beings exposed to contaminated groundwater and surface water, four different scenarios has been considered. Unacceptable risk is found for groundwater. Confirming that underground water resources are the most importantly affected by landfill contamination. The risk is sensibly higher when the landfill is operating with respect to the postclosure case where infiltration within the landfill body are minimized and, hence, the leachate loss from the bottom of the landfill are smaller. A properly functioning liner decreases the risk for groundwater, river and human health by a factor of about 30 in the configuration here analyzed.

Non-carcinogenic and carcinogenic risk are below the acceptable risk, however fish ingestion and dermal contact with contaminated water are found to be the most important exposure pathways for carcinogenic risk while toxics effects are mainly related with ingestion of contaminated vegetables. The Toluone resulted to be the most important chemicals for carcinogenic effects while Ammonia is the most responsible for non-carcinogenic adverse effects.

It is worth to note that the risk assessment approach here presented allows to compare the operating and postclosure landfill with properly working liner system with the case of sealing failure on the base of the effects upon human health and natural resources, such groundwater and surface water. Moreover, the approach permits to identify the most risky chemicals and subsequently drive the monitoring strategy and emergency plan.

The results here presented has been derived under the hypothesis of the worst case scenario where all the parameters used are taken in a way the results are conservative. Future works are planned for develop a general procedure that accounts for uncertainty and variability through a probabilistic risk assessment.

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