A GIS based approach to quantify and map human health risk related to landfill disposal and incineration of wastes.

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Introduction

Due to industrial and traffic emissions, agricultural activities and waste disposal facilities, many hazardous compounds are released into environment thus generating a potential hazard to human health and environment.
In European countries, industrial emissions are restricted and controlled by regulators and concepts such as Integrated Pollution Prevention and Control, Best Practicable Environmental Option, and Best Available Technology (Not Entailing Excessive Costs) are applied, in order to reduce environmental impact of industries. Essentially companies are not required to assess the risks posed by their emissions, but to assure that no emission limit values are exceeded.
The authorization procedure of industrial emissions through the standard based principles doesn't account the real site conditions and the characteristics of sensitive receptors. As a consequence, the standard based approach could sometimes not guarantee health for all the potential receptors or in the opposite case define limits to much restrictive in respect to the territory vulnerability.
On the other side the Environmental and Human Health Risk Assessment (EHHRA) is a scientific and rigorous procedure able to correctly evaluate the probability that adverse effects on the environment and/or the human health occur (or may occur) due to the exposure to one or more pollutants related to industrial pollution.
In order to perform environmental risk evaluation, a great attempt is generally assigned to determine risk on human health owing to exposure at carcinogenic or toxic substances, which may be present in air, soil, water, foods, as consequence of anthropic activities. Procedures for performing this type of assessments are regularly delineated by government agencies, such as U.S. EPA (United States Environmental Protection Agency), EEA (European Environment Agency) and by European Directives and national regulations; most of them are based on the National Academy of Sciences model introduced in 1983 (NAS, 1983).
A complete Environmental and Human Health Risk Assessment (EHHRA) requires the integration of information on environmental and chemicals database, inter and intra media dispersion models output, site description maps and demographic database. As a result, the designing and conducting analysis of the effects of contaminants on human health is a complex and time expensive procedure, particularly when the aim is to estimate risk in a geographical area characterized by the presence of several sources, exposure pathways and receptor typologies.
RISK-GIS is a Human Health Decision Support System developed in a GIS framework to support an expert user interested in assessing and managing such risk typologies for a territory characterized by the presence of several industrial sources, which, daily or accidentally, emit dangerous pollutants able to impact on different environmental media (air, surface or underground water,…).
In order to estimate potential human health risk, the proposed tool, RISK-GIS, employs an integrated, multimedia, multi-exposure pathways and multi-receptors risk model
The paper explores through some case studies the ability of spatial risk-based approach to produce a quantitative evaluation of the risk posed by industrial emissions taking into account the site and the receptor features.

The Human Health Risk Assessment (HHRA) Methodology

The aim of human health risk analysis is the calculation of the upper-bound excess lifetime cancer risk and noncarcinogenic hazards.
Risk estimation consists in the computation of the upper-bound excess lifetime cancer risk (*risk*) and noncarcinogenic hazards (*hazard*) for each of the pathways and receptors identified in the area of interest. Risk is defined as the probability that a receptor will develop cancer in his lifetime, assuming a unique set of exposure, model, and toxicity properties. In contrast, hazard is quantified as the potential for developing noncarcinogenic health effects as a result of exposure to COCs, averaged over an exposure period. It is worth noting that hazard is not a probability but, more exactly, a measure of the magnitude of a receptor's potential exposure relative to a standard exposure level.
The individual cancer risk of a receptor *j* set by exposure to multiple carcinogenic chemicals *i*, is calculated through the following equation:

$$Individual\_CancerRisk_j = \sum_i LADD_{ij} \cdot CSF_i$$

where:
$LADD_{ij}$ = Lifetime Average Daily Dose for a lifetime exposure of 70 years (mg/kg-day) through multiple exposure pathways
CSF_i = Cancer slope factor for COC *i* $(mg/kg\text{-}day)^{-1}$.
Comparing an exposure estimate to a Reference Dose (RfD), the potential for noncarcinogenic health effects resulting from exposure to a chemical is evaluated. A RfD is defined as a daily intake rate that is estimated to cause no appreciable risk of adverse health effects, even to sensitive populations, over a specific exposure duration (USEPA, 1989). Generally, the more the Hazard Quotient value exceeds 1, the greater is the level of concern. In spite of this, because RfDs do not have equal accuracy or precision, and are not based on the same severity of effect, the level of concern does not increase linearly as the quotient approaches and exceeds 1.
Based on similar COCs toxicological characteristics and additive health effects, the Hazard Quotient (HQ) for receptor *j* exposed to multiple chemicals *i*, is calculated as:

$$HQ_j = \sum_i \frac{ADD_{ij}}{RfD_i}$$

where:
ADD_{ij} = Average Daily Dose averaged for the exposure duration relative to the toxic *i* for the receptor *j* (mg/kg-d) through multiple exposure pathways
RfD_i = COC *i* Reference Dose (mg/kg-d).
Lifetime Average Daily Dose and Average Daily Dose represent the amount a person takes in as a result of exposure to a chemical in contaminated air, water, soil or food. The combinations of the potential pathways by which individuals can be exposed represent the exposure scenario for an individual. Human receptors may be exposed to COCs via multiple primary exposure routes, either directly or indirectly. The estimation of the exposure magnitude consists in the quantification of the potential dose that is of the quantity of agent that enters in contact with the human organism through the points of exchange with the environment (lungs, skin, etc.) in a specific interval time. The calculation of COC-specific exposure rates for each exposure pathway *k* to be considered, requires the estimation of chemicals media concentrations, the consumption rate, the receptor body weight, the frequency and duration of exposure. The generic equation used to calculate chemical intake ($LADD_{ij}$ for carcinogenic chemicals, ADD_{ij} for toxic chemicals) is:

$$I_{i,j}(x,y,z) = \sum_k \frac{C_{i,em} \cdot CR_{j,k} \cdot EF_{j,k} \cdot ED_{j,k}}{BW_j \cdot AT_{j,k}}$$

where:
$I_{i,j}\ (x, y, z)$ = Intake for COC *i* and class of receptors *j* (mg/kg-day)
$C_{i,em}$ = COC *i* concentration in exposure media (e.g., mg/kg for soil)
$CR_{j,k}$ = Consumption rate, the amount of contaminated medium consumed through the *k* exposure pathway per unit of time or event (e.g., kg/day for soil)

$EF_{j,k}$ = Exposure frequency (days/year)
$ED_{j,k}$ = Exposure duration (years), total time period over which contacts occur between receptor and COC
BW_j = Average body weight of the receptor *j* over the exposure period (kg)
$AT_{j,k}$ = Averaging time, the period over which exposure is averaged (days); for carcinogens, the averaging time is 25550 days, based on a lifetime exposure of 70 years; for toxics the averaging time is exposure duration expressed in days.
In order to calculate chemicals concentrations in various exposure media, procedures extracted from (USEPA, 1998) are usually adopted, that allow the estimation of the concentration of a chemical in an exposure medium in terms of the chemical concentration in the environmental compartment, by means of an inter-media transfer factor:

$$C(x, y, z)_{exposure} = f(TF,\ C(x, y, z)_{enviromedia})$$

where:
$C(x, y, z)_{exposure}$ = Concentration in exposure media
$C(x, y, z)_{enviromedia}$ = Concentration in environmental media
TF = Inter-media transfer factor from an environmental compartment to an exposure medium.
Inter-media transfer factor is usually expressed by an appropriate chemical-specific partition coefficient, which describes the physicochemical attraction of the contaminant for the environment and the exposure medium.
Concentration distributions in environmental media result from the application of contaminants fate and transport models or from measured data.

RISK-GIS: a GIS-based approach to human health risk assessment

The RISK-GIS tool is an integrated approach for assessing the risks to human health; it is able to manage all the steps of the above described methodology in a georeferenced framework operating in a GIS environment, in order to display maps of iso-dose and iso-risk contours. The tool evaluates cancer risks and hazard quotients in a geographical area characterized by multimedia contamination, potential multi-exposure pathways and several receptor typologies.
Figure 1 shows a block diagram that illustrates the architecture of the methodology to assess human health risk using RISK-GIS.
For each chemical of concern identified in the contaminated area, estimates of the concentrations must be defined for each environmental medium of interest (e.g. soil, ground water, surface water, sediment, air, vegetation). User may derive concentrations from two broad methods: direct monitoring (e.g. sampling and chemical analysis of media at the site coupled with summary statistics) or environmental modelling (e.g. mathematical modelling to predict contaminant concentrations in various media). In both cases the output of the analysis is a series of maps describing the distribution of the toxic and carcinogenic chemicals concentrations in the environmental contaminated media.
Chemicals environmental fate and transport models are implemented in the Gis tool so that the outputs of the models are imported into Gis and displayed as maps of distribution of concentration. The system graphical user interface allows the interaction with the different stages of the simulation, that are the data input (*pre-processing*), the run of the model and the output display (*post-processing*), taking advantage of Gis spatial analysis tools.
The exposure model computes, for each specific human receptor, the intake of a Chemical of Concern due to multiple exposure media and to multiple environmental media. In order to run exposure models it is necessary to input the characteristics of individuals. For each identified exposure scenarios, it is possible to select one up to 21 specific exposure pathways, including ingestion of different types of food, soil and water, inhalation of gas and particle, dermal contact with water and soil**.**

If data to describe variability and perform a sensitivity analysis are available, the tool finally calculates the probability distribution of risk by using a Monte Carlo analysis and the Gis displays risk maps through specific user-defined percentiles contours.
It’s worth noting that the power of the tool is especially its aptitude to examine several sources of contamination, COCs, pathways and receptors in a single system and its capacity to illustrate such in detail a specific territorial pattern in this way giving a complete picture of risks. The RISK-GIS results, displayed on georeferenced maps, can improve risks communication to all stakeholders (public administrations, industry operators, regulator agencies) and risk managers, in order to select options to reduce health risk and plan remediation actions.

Human Health Risk Assessment: Case Studies

The first case study explores the ability of risk-based approach to produce a quantitative evaluation of the risk posed by industrial emissions taking into account the real site and the receptor features.
The source of risk is represented by an air emissions releases from a waste incinerator plant located in the North of Italy, the emission stack is located in mixed area with residential, agricultural and industrial zones.
The Chemical of Concerns associated to waste combustion emission are toxic and carcinogenic compounds such as metals, PCB, PCDD/F, IPA and acid.
To take account of various typologies of receptors, the presence of two principal classes of receptors has been considered: the less vulnerable (healthy adult) and the most vulnerable (child).
The exposure pathway considered in this assessment include inhalation, dermal absorption from soil, ingestion of soil, vegetation, meat, egg, water and milk. In the simulation the receptor population is exposed to emissions for a 70-yr lifetime and is divided into three age groups: young children (up to 6 yr old, 15 kg average body weight) and adults (age 15-70 yr old, 70 kg).
Using the ISC3 (USEPA) air dispersion model implemented in RISK-GIS is possible to produce map of COCs concentration in air and estimate the deposition fluxes.
Multimedia models are applied to calculate total intake: atmospheric substances are partitioned to soil and vegetation and bioaccumulate in livestock (cows milk and meat). Concentrations of COCs in vegetables, eggs, milk and meat were calculated using bioaccumulation food-chain models.
As a first example of risk distribution maps generated by the tool, Figure 2 presents the map of cancer risk for adults due to waste incinerator contamination.
Examining results in the light of generally acceptable lifetime cancer risk range, 10^{-4} - 10^{-6}, the maximum human health risk estimated caused by waste combustion emissions for receptors living in the study area (2.3E10^{-7} for adults and children, 1.1E10^{-7} for infants) has to be considered absolutely acceptable.
The case study has been completed with a sensitivity analysis, the aim being to understand how risk estimates are dependent on variability in the factors contributing to risk.
The second case study concerns the implementation of a ambient permit emission system in a risk-based framework. Combing air dispersion modelling, GIS and the human health risk assessment procedure is possible to develop a tool able to support decision maker in toxic and carcinogenic air emission permit allocation with the purpose of guarantee the respect of human health.
The human health risk based permit emission mechanism sets limits or "caps" for each pollutant in order to guarantee the respect of risk targets for each receptor exposed by multiple emissions sources and COCs.
The first step of the procedure consists in evaluating and allocating the amount of emission credits for each emission sources based on the respect of human health risk target for each receptor potentially exposed.
Emission Sources that intend to exceed the limits may buy emissions credits from entities that are able to stay below their designated limits.

The Spatial Risk Based Emission Trading mechanism is an iterative procedure developed troughs the following steps:

- The carcinogenic emissions of k (1…t) COC released by the source j are evaluated as equivalent benzene $EF_j^{BENZ\_EQ} = \sum_{k=1}^{t} EF^k \bullet \frac{UR^k}{UR^{BENZ}}$ where UR is the Unit Risk representing the incremental cancer risk for a standard adult receptor exposed by a concentration of 1 **µg/m3**
- The Inhalation cancer Risk for each receptor i(x,y,z) exposed by multiple industrial sources emissions j (1…n) and k (1…t) Chemical of Concerns is evaluated with the following expression: $RISK_{TOT,i} = \sum_{j=1}^{n} EF_j^{BENZ\_EQ} \bullet UR^{BENZ} \bullet D_{i,j}$ where Di,j is the dilution coefficient of emission j at receptor i computed using Gaussian air dispersion models;
- For each receptor i (x,y,z) where RISK_Tot,i is greater then Risk_Limit,i
    - Selection of n sources j with a relevant contribution to total inhalation risk RISK_Tot,i ;
    - Under the assumption that each relevant air emission sources have the same right to pollute is possible to allocate the acceptable risk contribution to each sources as $ARISK_{j,i} = \frac{RISK_{LIMITi}}{n}$
    - The difference between RISKi,j and the allocated risk ARISKj,i represents for each sources the Credit or Debit;
    - Conversion of Risk credit/debit in air Emission Factor credit/debit of equivalent benzene for each sources j

Conclusion

The estimates of risk for human being caused by antropic activities is profitably done if the complete procedure of risk calculation can be adopted. The paper shows that RISK-GIS code employs a risk calculation detailed procedure because may consider an integrated, multimedia, multi-exposure pathways and multi-receptor model. The case study discussed puts in evidence benefits, in terms of problem knowledge, quantitative risk evaluation of actual contamination state and of alternative scenarios, that the code can give to an assessor interested in assuming decisions for safeguarding citizen health.

References

- Bagli, S.; Morra, P.; Spadoni, G. The EHHRA tool: a decision support system for assessing and managing human health risk from industrial activities. Proceedings of 11th International Symposium Loss Prevention. Praha; 2004
- Morra P, Bagli S, Spadoni G. The analysis of human health risk with a detailed procedure operating in a GIS environment. Environ Int. 2006 May;32(4):444-54. Epub 2005 Dec 13.
- NAS (National Academy of Sciences). Risk Assessment in the Federal Government: Managing the process. National Academy Press. Washington, D.C. 1983
- USEPA (United States Environmental Protection Agency). Risk Assessment Guidance for Superfund: Volume I. Human Health Evaluation Manual (Part A). OERR. Washington, D.C. 1989
- USEPA (United States Environmental Protection Agency). Human Health Risk Assessment Protocol for Hazardous Waste Combustion Facilities (vol.1). 1998

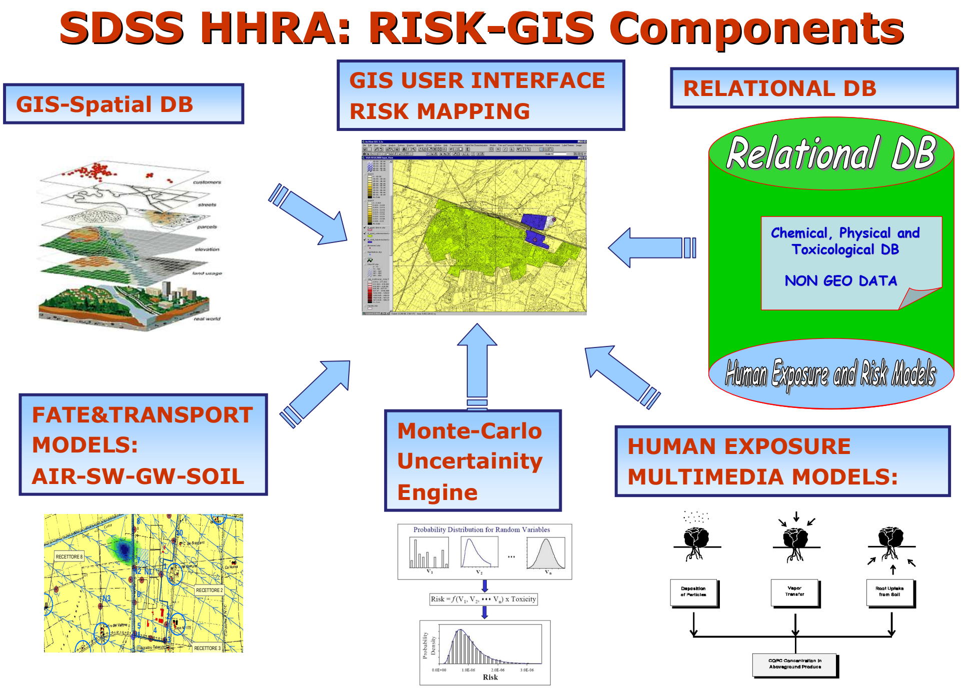

Figure 1 – RISK-GIS framework

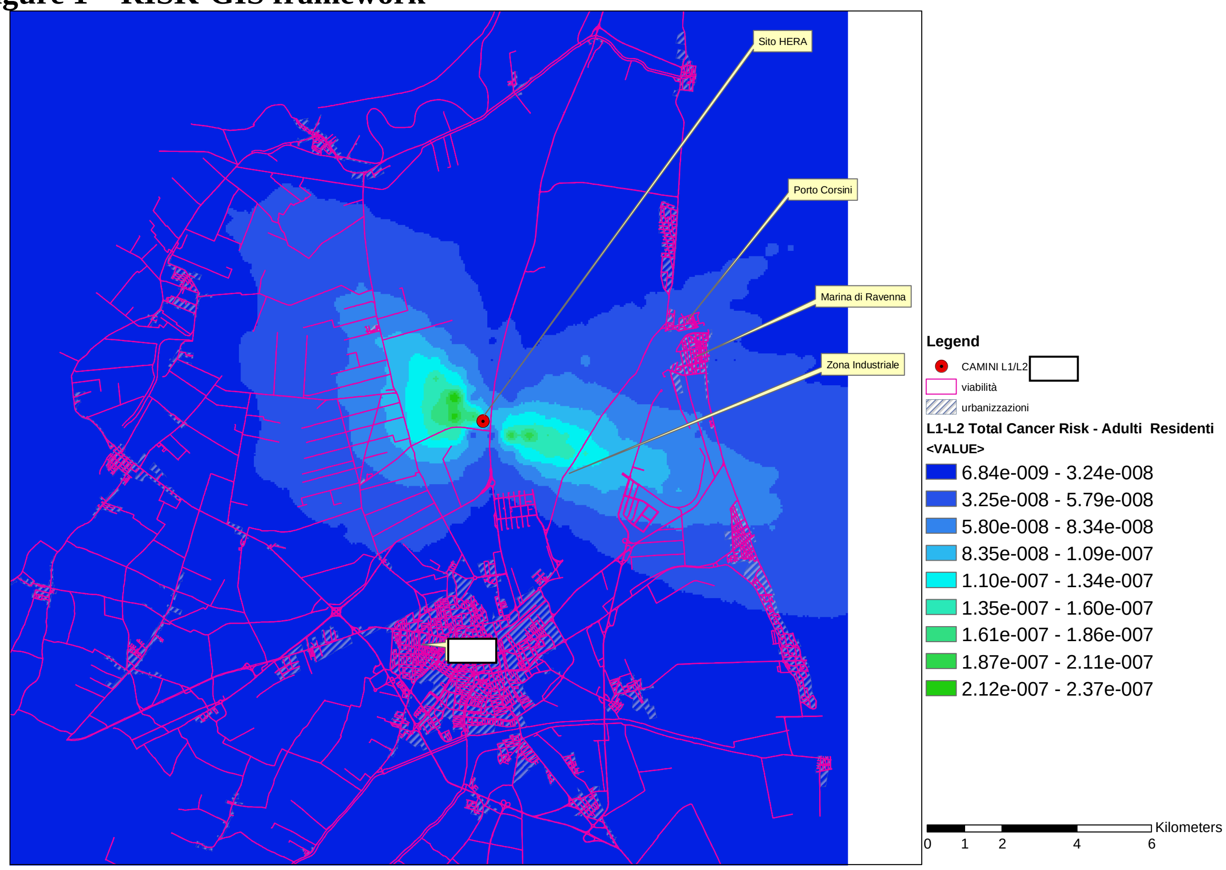

Figure 2 – Total Cancer Risk related to incinerator emission for Adult resident receptor