Multi-risk evaluation is a relatively new field, until now developed only partially by experts with different backgrounds. The EC FP6 NARAS project initiated some consideration and reflection on this topic. As mentioned by Durham, a joint analysis and quantification of all the anthropogenic and natural risks which can affect a territory (multi-risk approach) is a basic factor for development of a sustainable environment and land use planning as well as for competent emergency management before and during catastrophic events. This is the aim of this publication that will present ideas and concepts: - report the principles and rationales that stand behind a procedure for multi-risk assessment; - provide a description of the most advanced procedures generally adopted to estimate individually natural and anthropogenic risks representing major threats for Southern Europe; - tackle directly the problem of multi-risk assessment applying innovative procedures and protocols to the case study of a town close to Naples (Casalnuovo).
Principles
of multi-risk assessment

Interaction amongst natural and man-induced risks

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FOREWORD

Fatalities and economic losses due to natural catastrophic events have increased in the last decades. This is not only due to the growth of population density in hazard risk zones, but also to the consequent and concomitant increase of possible “cascade effects”.

Assessment and mitigation of the impact of catastrophic events in a given area require innovative approaches allowing a comparison of different risks and accounting for all the possible cascade events. Ranking of the typologies of risks affecting a given area can hardly be made because presently available scenarios are often qualitative; they are related to one reference event and rarely account for the related uncertainties. Moreover different types of risks (as volcanic, fast mass movements, floods, earthquakes) are often estimated using different procedures so that the produced results are not comparable.

These problems can be overcome through the development of new methods which can provide reliable quantitative estimation of individual and coupled events. Compared to classical analysis of single risks, these methods may provide a formal scheme to compare and rank different kinds of hazardous phenomena (natural, industrial, etc...), and account for “cascade effects” that are usually neglected in single risks analysis. Therefore the multi-risk approach is not an alternative to single risk analysis. In fact, as shown in this volume, probabilistic single risk analysis is a necessary pre-requisite for a multi-risk analysis. True multi-risk analysis is a widely interdisciplinary field; specialists of each natural and anthropogenic hazard need to work together in order to understand the long-term evolution of the governing physical system and the various triggering mechanisms.

Several new ideas were gathered and developed in the European project NaRas-Natural Hazard Risk Assessment, funded under the European Union’s Sixth Framework Programme of research (FP6).

We hope that this document, which reflects the main outcomes, will help to clarify the key ideas around the concepts of multi-risk. It should as well stimulate further development in this field of science and contribute to “prevent the avoidable and mitigate the unavoidable”.

Elisabeth Lipiatou, Denis Peter
Climate Change and Environmental Risks Unit
Directorate-General for Research
European Commission
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1. Introduction and objectives

1.1. Purpose of document

Several risks impend on the environment, on public and private properties, on strategic and priceless infrastructures in any inhabited area of our planet. They are generated by different sources, both natural and anthropogenic, and have different relevance depending on the synergy between the generated events and on the peculiar interaction with the region where they break out.

The evaluation of risks related to different sources is generally done through independent analyses, adopting disparate procedures and time-space resolutions. In most of cases, only qualitative estimates of the risk level are available. Such a strategy of risks evaluation has some evident major drawbacks: 1) it is difficult, if not impossible, to compare risks of different origins; 2) the implicit assumption of independence of the risk sources leads to neglect possible interactions among threats and/or ‘cascade’ effects. In practice, this means that a potential ‘multi-risk’ index could be higher than the simple aggregation of single risk indexes calculated considering each source as independent from the others.

A joint analysis and quantification of all the anthropogenic and natural risks which can affect a territory (multi-risk approach) is a basic factor for the development of a sustainable environment and land use planning as well as for a competent emergency management before and during catastrophic events (Durham, 2003). Multi-risk evaluation is a relatively new field, until now developed only partially by experts with different backgrounds (engineering, statistics, seismology, toxicology etc.). Among the few works on this field we quote the UNDRO study (1977), the KATANOS report (1995), Granger et al. (1999), Van Westen et al. (2002), Ferrier and Haque (2003), Grunthal et al. (2006), Blong (2003). However the problem of interaction among different threats is not approached, even in these cases.

Objective difficulties in the quantification of risk and thus of multi-risk exist. The first is that scientists of various disciplines do not use a common terminology. In some cases scientists dealing with different types of environmental risks assign different definitions even to the same term. Other difficulties are mostly due to different practices (qualitative and quantitative) and spatial and temporal resolutions that make hard the comparison among different risks.

In this document, we propose a new quantitative procedure for multi-risk assessment that makes easier the comparison among different threats and accounts for possible triggering effects.

We consider only the major threats typical for Southern Europe, which were the objectives of the EC FP6 NaRaS (Natural Risk Assessment) Project. Forest fires, snow avalanches, wind storms, heat waves are not specifically considered, although the general methodology we propose can be applied to evaluate risk related to these adverse events.

In this document, we propose a new quantitative procedure for multi-risk assessment that makes easier the comparison among different threats and accounts for possible triggering effects.

In this part of the document, a clarification of the used terminology and a homogenization of the concepts used by the scientists and practitioners in the different risks areas are proposed. This effort does not aim at providing ‘the solution’ of the lack of homogeneity in terminology, but just at being a useful reference to clarify the meaning of the terms used here.

At the end of part 1, we report the principles and rationales that stand behind our procedure for multi-risk assessment. In part 2, a short description of the most advanced procedures generally adopted to estimate individually natural and anthropogenic risks representing major threats for Southern Europe is provided. In part 3, we tackle directly the problem of multi-risk assessment applying innovative procedures and protocols to the case study of a town close to Naples (Casalnuovo).

The multi-risk problem is split in two distinct phases: in a first phase, the whole set of risks is homogenized to facilitate their comparison ranking; in the second phase, we explore in detail possible “triggering” effects, showing how they can increase significantly the risk in a specific site. We want to underline that the logical sequence of the multi-risk procedure is contained in Parts 1 and 3, which are self-consistent. Part 2 contains several details on the actual way to compute different parameters. Anyway it can be omitted by readers who are interested only in the logical process we have followed.

1.2. Definitions and terminology

Different terminology and definitions of the same terms are used in the practice of risk evaluation for natural and anthropogenic risks. In our work we define the meaning of each term to make easier a com-
parison with the use made in other disciplines. The definitions we have adopted are the following:

**Risk source or hazard:** anything that can potentially generate adverse events and consequently create damage to the population and/or environment. It is therefore a concept related only to the intrinsic characteristics of a substance, a plant or of a physical/geological status of a site.¹

**Adverse event:** anything produced by a risk source in a certain area that can generate phenomena with potentially adverse consequences. The adverse event can be due to a risk source located inside or outside the site where the event takes place.

**Synergistic (adverse) event:** a series-parallel sequence of adverse events generated by different sources. For example, an earthquake and a landslide generated by it.

**Event (in a Bayesian event tree):** a specific situation of the evolution of a hazard identified as a branch of the tree and characterized by a conditional probability.

**Phenomenon:** one of the forms (many are possible) under which the adverse event causes damages. It is usually measured by the parameter of intensity.

**Intensity:** the measure of entity with which a phenomenon can be manifested or cause damage.

**Hazard index (or Probabilistic hazard):** the probability that a certain adverse event generating a phenomenon of a given intensity will occur in a given area in a given time interval. Consequently, the hazard index is evaluated by taking into account the characteristics of the risk source, the location it refers to and the physical process of intensity diffusion from the risk source location to the investigated area (see the term exposure).

**Value (at risk):** it measures the total potential loss due to an adverse event in a given area. It can be expressed in human casualties, either in economic or conventional terms (since it is difficult to express heritage or environmental losses monetarily). It is sometimes expressed as a percentage of the total value of the area. It depends on the various activities (human, cultural, economic) as well as on the environmental characteristics of the referred area.

**Vulnerability:** it is the fraction of the total value at risk that could be lost after a specific adverse event.

**Damage:** it synthesizes the different adverse consequences caused by adverse events and related phenomena. Its value can be obtained by multiplying the value at risk and the vulnerability.

**Exposure:** the way a vulnerable damage receptor comes into contact with a phenomenon generated by a risk source. The quantification of exposure is included into the hazard index and vulnerability calculation.

**Scenario:** a representation (often only qualitative) of one or more linked adverse events causing and/or caused by threatening phenomena. Several scenarios can be identified for each adverse event. A quantitative estimate of each of them can be achieved using Bayesian methods.

**Risk:** the non-normalized probability that a negative consequence (that is, a certain type and degree of damage) can occur in a given period of time following a specific adverse event. Different mathematical definitions are applied according to the situation. For environmental and natural issues, risk factors can be conveniently defined as a function of the probability that a certain event will occur and of the extent of the damage caused to man, environment and objects. Thus, it can be quantified by:

\[
\text{Risk} = (\text{probability}) \times (\text{resulting degree of damage}) \tag{1}
\]

The following expression is generally used to quantify risks due to natural events:

\[
\text{Risk} = (\text{hazard index}) \times (\text{vulnerability}) \times (\text{value at risk}) \tag{2}
\]

that is equal to the first expression when using the above given definitions. This definition basically coincides with that provided by the European Community (EN 1050, 1996) which indicates risk related to a specific source (or hazard) as a function of the magnitude of the potential damage that may result from the considered hazard and from the probability that it will occur (also a function of the frequency and duration of the exposure, of the probability it will occur and of the possibility to avoid or limit the damage).

¹ For instance, a toxic substance that can be dangerous for human health (i.e. it is an hazard or risk source) does not produce a risk if vulnerable receptors are not exposed to it.
It follows that risk is clearly a non-normalized probability because it has a lower limit (which is zero when there is no appreciable possibility of an adverse event occurring or when the degree of resulting damage is practically null), but not necessarily an upper limit. The presence of an upper limit (equal to one) is possible only if the resulting degree of damage in equation 1, or the value at risk in equation 2, is provided as percentages of the area’s total value. A synthetic example of our terminology is reported in Table 1.

Table 1. The following table reports some examples of risk source, adverse event and related phenomena.

<table>
<thead>
<tr>
<th>Risk Source</th>
<th>Adverse event</th>
<th>Phenomenon</th>
<th>Unit of measure of phenomenon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faults</td>
<td>Energy release</td>
<td>Ground oscillations</td>
<td>m/s²</td>
</tr>
<tr>
<td>Industrial plants</td>
<td>Toxic substance release fires Explosions</td>
<td>Toxic cloud/contamination Thermal or stationary flow Pressure wave</td>
<td>mg/m³ kW/m² Pa</td>
</tr>
<tr>
<td>Volcano</td>
<td>Pyroclastic flow Ash fall ...</td>
<td>Toxic cloud Pressure wave Static vertical loading</td>
<td>mg/m³ Pa</td>
</tr>
<tr>
<td>Unstable slope</td>
<td>Solid mass movement</td>
<td>Pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>River</td>
<td>Flood</td>
<td>Water thickness Water discharge</td>
<td>m m³/s</td>
</tr>
</tbody>
</table>

It is noteworthy that different adverse events can be associated to a specific risk source and that different phenomena can be due to a same adverse event.

Note that the introduction of the concept of probability in risk analysis is useful for many important reasons:

1. It allows an immediate gradation of environmental risks and may even facilitate comparison and management of events of a different nature (including terrorist attacks).
2. It can be used as supporting tool during the decision-making phase and, in particular, to perform the cost/benefits analyses of management strategies.
3. It allows the definition of the fundamental concept of societal “acceptable risk”, i.e. the level of risk that a community is willing to accept. It establishes an objective reference both for land use planning and for a selection of risk mitigation actions based on a cost/benefit analysis.

1.3. Procedure for multi-risk assessment

The purpose of multi-risk analyses is basically to establish a ranking of the different types of risk taking into account possible cascade effects i.e. the situation for which an adverse event triggers one or more sequential events (synergistic event). The procedure for environmental risks assessment that includes the risk of multi-hazards synergy is illustrated in this paragraph by identifying the main steps to be followed to estimate the multi-risk index.

The main steps are those usually utilized to perform an environmental risk assessment with some peculiar differences:

1. the estimate of the multi-risk index has to take into account possible cascade and/or triggered related adverse events.
2. A common time frame and area under threat must be used.
3. A reference expected damage has to be defined “a priori”.

The general procedure for multi-hazard assessment is reported in the following scheme. One peculiar aspect of this procedure is the creation of a set of scenarios correlating adverse events from different
sources. For each “risk scenario”, adverse events, phenomena and damage will be correlated in a series-parallel sequence of happenings through an “event-tree”. Each branch of the event tree will be quantified by a probabilistic analysis of the “history” of the events, the vulnerability and the exposed values of the specified targets. At last a final risk will be estimated.

The procedure is summarized in Table 2.

A brief explanation of each step is reported in the following.

**Identification of hazards/Risk sources**

Each natural and anthropogenic hazard must be identified. Possible triggering of different adverse events must be considered (multi-hazard approach). For each hazard, the related adverse events, and the phenomena must be identified. Once the database of hazards, adverse events and phenomena is available, a set of scenarios has to be defined by identifying the possible chain of correlated events. The events tree is a tool that can be used in this step in order to mimic the possible chain of events. It allows a straightforward evaluation of the probability of a given chain of events, hence being the premise of a quantitative evaluation of risk.

**Exposure and vulnerability analysis**

A complete vulnerability analysis must start from a careful identification of the assets under threat. They generally include:

- a) man made structures, infrastructures and buildings;
- b) cultural heritage;
- c) life-lines;
- d) animals and humans;
- e) agricultural and forest areas;
- f) ecosystems.

Table 2. Procedure for multi-risk analysis.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Identification of hazards/risk sources.</td>
<td></td>
</tr>
<tr>
<td>1.b Characterization of adverse events and its propagation path.</td>
<td></td>
</tr>
<tr>
<td>2. Exposure and Vulnerability analysis.</td>
<td></td>
</tr>
<tr>
<td>2.b Phenomenon intensity distribution (e.g. ground acceleration, pressure waves, distribution of chemical substance concentration for various areas, thermal flow, etc.).</td>
<td></td>
</tr>
<tr>
<td>3. Risk estimate.</td>
<td></td>
</tr>
<tr>
<td>3.b Estimate of the entity of damage.</td>
<td></td>
</tr>
</tbody>
</table>
| 3.d Comparison between the multi-risk value and the “acceptable risk”.

The evaluation of vulnerability of the first three categories is generally made through the computation of vulnerability functions enabling to assess the distribution of the expected damage in each typology of buildings for each expected phenomenon. Vulnerability functions should be estimated both for single adverse events and for cascades of adverse events. For example in the seismic case they should be computed for a single adverse event of a given intensity or/and for a sequence of adverse events. For combined seismic and volcanic adverse events they should consider the effects ground acceleration of
structures under a vertical load due to accumulating ashes, etc.
Humans, animals, and ecosystems have a vulnerability due to direct contact with the phenomenon (exposure to toxic substance, direct contact with a flood surge or a tsunami wave) and a vulnerability due the impact of damaged structures (collapses of parts or whole buildings, breakdown of bridges, lifelines, industrial components, etc.).
A complete evaluation of population vulnerability requires knowledge of the percentage of the total inhabitants residing in buildings of different vulnerability, in industries, working in dangerous situation, and the time distribution during the day. Statistical models of people distribution during each day of the week and in different seasons are a way to get reliable information on the vulnerability of the population. Each additional information (age distribution, percentage of unable population, etc.) increases the reliability of the model.

- **Risk estimate**
  For the multi-risk comparison it is useful the identification of a common reference damage for all the single risks, for instance the risk of having a number of casualties. In fact once the kind and intensity of the reference damage has been selected, different risks can be ranked on the basis of their probability to originate the reference damage. This may overcome the problem of assigning a monetary value to human life. This is needed if we want to compare risks to damage structures or infrastructures with risks for human life.
  The sequence of proposed steps is preceded by the characterization of the investigated area and by fixing the time interval of reference: the extent of the area is defined case by case, since the nature of the surrounding areas (type and number of vulnerable territorial and environmental elements) and the extension of the consequences due to the events may induce to expand or reduce the investigated area. The referring time interval is chosen depending on the final goal of the risk analysis; for instance, the time interval can be set to decades for land use planning, or few hours/days to manage an ongoing emergency.
2. Analysis of risks induced by a single source

The procedures for estimate of hazard and risk from different source typologies are hereafter described. The details of the application of Bayesian Tree procedures to a quantitative estimate of volcanic and industrial risks and of the relative uncertainties will be shown. The discussion is focused on the Italian situation. It shows in details the preliminary single risk assessments made for our multi-risk assessment case study of Casalnuovo.

2.1. Seismic risks

2.1.1. Introduction

Earthquakes, for severity and widespread impact, are one of the most disastrous events of natural origin that characterize Southern Europe. For the time being, there is not a unique approach for seismic hazard/risk assessment at a global or European scale. Here, we report the case of Italian territory, because it represents one of the most advanced procedures adopted in Europe. Italy is a country of high seismic risk, having a relatively high earthquake frequency and highly vulnerable buildings and infrastructures, partially due to the important historical heritage. For these reasons, a constant updating of seismic hazard/risk assessment for the whole national territory is essential for risk mitigation. This can be achieved through:

- the construction of new buildings of low seismic vulnerability, i.e. characterized by a low tendency to undergo a certain level of damage when a seismic event of a given intensity takes place;
- the seismic reinforcement of old buildings which were designed and constructed without anti-seismic criteria, even though located in areas characterized by a high seismic hazard.

In the following pages, an overview of current estimate of seismic hazard for the national territory will be provided, by reporting the procedure, the method and the results, in terms of maps, tables and graphs, of the Working Group of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) in charge of the production of the most recent version of the map of seismic hazard in Italy (Gruppo di Lavoro (2004), http://zonesismiche.mi.ingv.it).

2.1.2. The seismic hazard map of Italy

The current classification of the Italian territory in terms of seismic hazard was defined starting from the criteria set up by Italian laws; they establish that seismic areas are classified into 4 classes defined according to the maximum ground acceleration (amax) having a 10% probability of being exceeded in 50 years. It also established the responsibility of the Regional Governments to modify the details of the distribution of the seismic hazard in each Region with respect to the national map provided by the National Civil Protection. The responsibility for the National seismic hazard map has been given to INGV (Istituto Nazionale di Geofisica e Vulcanologia). The new seismic classification of the Italian territory was compiled in terms of value of amax referred to sites on rocks or very rigid soil (characterized by values of \( V_{s30} > 800 \) m/s, including possible shallow altered layers with maximum thickness of 5 m). Conversely, identification of possible amplifications of ground acceleration due to local effects, is under the responsibility of the Regional Governments.

Relevant data

The basic database used for the compilation of the new map of seismic hazard was the Catalogue of Italian earthquakes (CPTI). The most recent version of such a catalog (CPTI2) was produced during the activity of the INGV Working Group, updating the older one with the inclusion of all the instrumental data available since 1999. Homogeneous values of magnitude were determined (Msp) for all the events in the Catalogue. These data were used in combination with empirical laws of energy attenuation with epicentral distance for the Italian territory (Sabetta e Pugliese, 1996) to calculate expected ground acceleration in a given site.
Another source of preliminary data relevant to the evaluation of the seismic hazard was the information related to the identification of the main tectonic earthquake sources in Italy (seismogenic zoning). A new map was elaborated, called ZS9 (Figure 1). A total of 42 seismogenic zones were identified. Six of them were considered to not give a significant contribution to the seismic hazard in Italy.

Figure 1. Seismogenic zonation ZS9.

In each zone a seismogenic layer is defined as the depth interval producing 90% of the events that fall within that zone. The upper and lower limits of the seismogenic layer were thus identified at the depth that included a number of events equal to 5% and 95% of the total. An “efficient depth” is defined as the depth correspondent to the main modality of the frequency distribution of the events. For operational reasons focal depths have been gathered into four classes only (Figure 2).
The mechanism of prevalent faulting (Figure 3) is defined the mechanism having the maximum probability of characterizing future significant earthquakes. It was obtained by expressing the mechanism itself through three typologies “normal” “inverse” “strike-slip (right and left)”. A fourth typology “non determined” was added for the cases where the data were not sufficient for a definite determination. The assignment to a given typology using the “angle of rake” was made on the basis of the simple empirical criteria reported in Table 3.

Table 3. Definition of the mechanism of prevalent faulting.

<table>
<thead>
<tr>
<th>Prevalent Mechanism</th>
<th>Rake angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>&gt;225 (-135), &lt;315 (-45)</td>
</tr>
<tr>
<td>Inverse</td>
<td>&gt;45, &lt;135</td>
</tr>
<tr>
<td>Passing left</td>
<td>&lt;45, &gt;315 (-45)</td>
</tr>
<tr>
<td>Passing right</td>
<td>&gt;135, &lt;225 (-135)</td>
</tr>
</tbody>
</table>
Methodology
The seismic hazard was evaluated using standard methods of common use. A logic tree was used, aimed at the exploration of uncertainties, mostly of epistemic type, relative to:
1. determination of the intervals of completeness of the catalogue of the earthquakes;
2. determination of the seismicity rates;
3. modality of determination of the maximum Magnitude;
4. energy attenuation with distance and its attribution to regional effects.

Relations of attenuation of ground motion
The laws of seismic energy attenuation with the distance allow the evaluation of the seismic hazard by transferring the contribution of each zone to the site, in terms of seismogenic potential. The INGV Working Group used the data from the most recent earthquakes to check the attenuations of amax defined both on a national scale (Sabetta and Pugliese, 1996), and on the European scale (Ambraseys et al. 1996). This was made using epicentral distances calculated in an appropriate way and the modifications for the prevalent focal mechanisms introduced by Bommer et al. (2003). The result was the impossibility of having a coherent behaviour representative of regional and local situations. The INGV Working Group tried then to use a rule of scale determined on regional basis on the assumption to get a more consistent data set in this way.
The regional rule of scale used in the work of the INGV contains information on the propagation only for some macrozones of the Italian territory. For the portions of territory where a regional rule of scale was not available, the problem was solved by using the results obtained for some macrozones with similar crustal characteristics.

This procedure implies different levels of reliability for the various zones of the national territory. To mitigate this effect the INGV Working Group decided to introduce some alternatives, some of them linked to the focal depth, in two branches of the logic tree.

Two different regional branches were considered as alternatives. In each of them a different macrozonalization of the national territory was examined:
- regional branch A (Figure 4a);
- regional branch B (Figure 4b).

Figure 4. Attribution of the relations of regional attenuation at the ZS in the two branches of the logic tree a) REG branch A; b) REG branch B. The classes 1.1, 2.1, 3.1 and 4.1 identify ZS in which are localized the events used for the definition of the rule of scale; the classes 1.2, 2.2, 3.2 and 4.2 indicate ZS to which the relations of attenuation were associated on the basis of analogies in the propagating behaviour.

In the Regional branch A, a depth of 10 km was adopted for all the seismogenic zones except those related to volcanic activity where a depth of 4 km was assumed (Figure 5a). In the Regional Branch B, average depths were estimated for each seismogenic zone (Figure 5b).
Determination of the intervals of completeness of the catalogue of earthquakes

Three different Magnitude scales are used in the Catalogue of Italian Earthquakes. They are the Moment Magnitude (Mw), the classical Ms Magnitude and a Magnitude Msp. The latter is a hybrid parameter used only to simplify the application of the Sabetta and Pugliese (1996) attenuation law. Msp has the same value as Ms for Ms ≥ 5.5; it has the same value as the local Magnitude for Ms < 5.5.

The relationships among this magnitude are not linear. The INGV Working Group proceeded, therefore, to determine the classes of magnitude for each M. These classes were defined in such a way as to not have a variable dimension and avoiding the overload of some classes, cumulating two “peaks” of earthquakes in one class of magnitude.

Mw was assumed as reference. It was divided in 12 classes of constant width of 0.23, in the range Mw = 4.76 ± 0.115 to Mw = 7.29 ± 0.115 (Table 4 and Figure 6).

Table 4. Comparison among the central values of the Mw, Ms and Msp classes and of Io (Intensity in the MCS scale).

<table>
<thead>
<tr>
<th>N.</th>
<th>Mw</th>
<th>Ms</th>
<th>Msp</th>
<th>Io(MCS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.76 ± 0.115</td>
<td>4.3 ± 0.15</td>
<td>4.49 ± 0.14</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>4.99 ± 0.115</td>
<td>4.6 ± 0.15</td>
<td>4.77 ± 0.14</td>
<td>6/7</td>
</tr>
<tr>
<td>3</td>
<td>5.22 ± 0.115</td>
<td>4.9 ± 0.15</td>
<td>5.05 ± 0.14</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>5.45 ± 0.115</td>
<td>5.2 ± 0.15</td>
<td>5.33 ± 0.14</td>
<td>7/8</td>
</tr>
<tr>
<td>5</td>
<td>5.68 ± 0.115</td>
<td>5.5 ± 0.15</td>
<td>5.61 ± 0.14</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>5.91 ± 0.115</td>
<td>5.8 ± 0.15</td>
<td>5.89 ± 0.14</td>
<td>8/9</td>
</tr>
<tr>
<td>7</td>
<td>6.14 ± 0.115</td>
<td>6.1 ± 0.15</td>
<td>6.17 ± 0.14</td>
<td>9</td>
</tr>
<tr>
<td>8</td>
<td>6.37 ± 0.115</td>
<td>6.4 ± 0.15</td>
<td>6.45 ± 0.14</td>
<td>9/10</td>
</tr>
<tr>
<td>9</td>
<td>6.60 ± 0.115</td>
<td>6.7 ± 0.15</td>
<td>6.73 ± 0.14</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>6.83 ± 0.115</td>
<td>7.0 ± 0.15</td>
<td>7.01 ± 0.14</td>
<td>10/11</td>
</tr>
<tr>
<td>11</td>
<td>7.06 ± 0.115</td>
<td>7.3 ± 0.15</td>
<td>7.29 ± 0.14</td>
<td>11</td>
</tr>
<tr>
<td>12</td>
<td>7.29 ± 0.115</td>
<td>7.6 ± 0.15</td>
<td>7.57 ± 0.14</td>
<td>11/12</td>
</tr>
</tbody>
</table>
For each class of magnitude and for each seismogenic zone, an interval of completeness was defined as the time interval where the catalogue is complete. The evaluation of the interval of completeness was carried out using two different approaches: an historical approach (CO-04.2) and a statistical one (CO-04.4).

Adoption of the Mmax value
The Mmax values represent traditionally an element of caution in the estimate of seismic hazard. In fact it is adopted to account for the possible occurrence of events of M higher than that of the events reported in the Catalogue. This choice reflects a poor knowledge of the seismogenic potential of a region. In fact, it is especially useful in regions with medium-low seismicity and/or poorly investigated. The Mmax value is determined with different statistical approaches. Often the difference between the adopted Mmax and the maximum value proposed by the catalogue (MmaxCPTI2) is very high. Two sets of Mmax values were identified: a) one calibrated, exclusively, on seismologic and geological data, (Mmax1); b) one of more selective type (Mmax2). Each set was determined initially in terms of Mw; Ms and Msp were subsequently calculated.

Determination of seismicity rates
The seismicity rates are determined, for each class of magnitude, dividing the corresponding number of earthquakes by the corresponding interval of completeness. These rates, determined in the hypotheses that the seismicity is stationary, are practically models of earthquake recurrence and, by definition, they are assumed to hold for the whole time interval. Consequently, the definition of the intervals of completeness are a crucial step in the procedure of hazard evaluation. If the seismicity of a given area is really stationary, it may be sufficient to use a reduced time interval (for example two hundred years) to get a fairly reliable estimate of seismicity rate. Conversely, if the seismicity is not stationary, the adoption of a too short time interval may result in inadequate calculated rates.

The seismicity rates have been determined through two different modalities of calculation. They are individual rates (activity rates) and relations such as truncated Gutenberg-Richter (GR rates). The Mmax1 and Mmax2 set were used in combination with activity rates and GR rates. The differences between the total number of earthquakes in CPTI2 and the total number of virtual earthquakes estimated from the seismicity rates are shown in the 4 right-hand side columns of the Table 5.
Table 5. Number of earthquakes in CPTI2 and of the virtual earthquakes estimated from the seismicity rates.

<table>
<thead>
<tr>
<th></th>
<th>CPTI2 (ZS)</th>
<th>CO-04.2</th>
<th>CO-04.4</th>
<th>CO-04.2</th>
<th>CO-04.4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AR</td>
<td>AR</td>
<td>GR</td>
<td>GR</td>
<td></td>
</tr>
<tr>
<td>Mw</td>
<td>5.91</td>
<td>121</td>
<td>74</td>
<td>95</td>
<td>149</td>
</tr>
<tr>
<td></td>
<td>6.14</td>
<td>64</td>
<td>38</td>
<td>47</td>
<td>85</td>
</tr>
</tbody>
</table>

Evaluation of amax

The amax distribution with 10% probability of being exceeded in 50 years was calculated with the code SEISRISK III, by using, with the relevant data, also the procedures and the choices discussed in the previous sections.

Several alternatives of prevalently epistemic character were explored with a logic tree approach. In particular alternatives were explored related to:

a) Intervals of completeness of the catalogue;
b) Modalities of Mmax determination;
c) Modality of calculation of seismicity rates;
d) Laws of attenuation of ground acceleration.

The branches of the logic tree and the weight adopted are described in Figure 7. The weights were applied to each branch in its set.

As required by the Italian norms, evaluations of amax were carried out using a grid of points with intervals of 0.05°; the results were given in units gravity acceleration (g), and represented by color strips with intervals of 0.025 g.

With reference to the branches of the logic tree, 16 independent runs were carried out. Then the distribution of the median was calculated, using of the provided weights, and represented in a conclusive map. The map representing the 90th percentile of the peak ground acceleration in the next 50 years is reported in Figure 8. It gives an overall picture of seismic hazard in the whole Italian territory where amax ranges from a minimum of 0.03 g to a maximum of approximately 0.3 g.
Figure 8. Conclusive Map of seismic hazard (amax with 10% probability of being exceeded in 50 years), obtained as median of the 16 maps correspondent to the 16 branches of the logic tree with the weights specified in Figure 7.

This map represents a basic document for the estimate of seismic risk but its application has a lot of limits. Risk assessment requires the evaluation of the vulnerability of edifices on the whole Italian territory, and some models to assess the damages. The vulnerability is a function of different aspects of the ground motion, not only of ground acceleration (amax). For example, vulnerability certainly depends on the dominant spectrum of the seismic oscillations that is not considered in the official hazard map. Moreover, an unbiased risk assessment requires a careful evaluation of the site effects that can modify substantially the expected ground motion estimated from the National hazard map. As regards the damages, some empirical rules are adopted to estimate the damages as a function of the ground motion for different types of buildings, and to calculate how these damages can induce the death of human beings. Some of them will be used to the practical example reported in Part 3.

At European level some interesting and complete risk assessment studies have been carried out only for very few selected infrastructures. A complete risk assessment at national scale is still missing. This implies that, in many locations we can estimate the seismic risk only making use of strong assumptions.
2.2. Volcanic risks

2.2.1. Methodology: the BET model

One of the most recent and comprehensive quantitative procedure to assess volcanic hazard and risk is based on the concept of Bayesian Event Tree (BET hereinafter) (Marzocchi et al., 2004, 2008; Newhall and Hoblitt 2002; see also Neri et al., 2008). BET is a useful framework for discussing, from a probabilistic point of view, all the relevant possible outcomes of a volcanic crisis. Basically, an event tree is a tree-like representation of events (see Figure 9) in which branches are logical steps from a general prior event through increasingly specific subsequent events (intermediate outcomes) to final outcomes. In this way, an event tree shows the most relevant possible outcomes of volcanic unrests at a progressively higher degree of detail. BET or similar models have positively been applied to some volcanic crisis in different volcanic areas, such as Mount St Helens, Mount Pinatubo, Soufriere Hills (Monserrat), Popocatepetl, Guagua Pichincha and Tungurahua. The main advantages of the ET scheme consist of its intrinsic simplicity and of providing a quantitative estimation of any kind of volcanic hazard and individual risk. A detailed description of BET can be found in Newhall and Hoblitt (2002), Marzocchi et al. (2004, 2008). Here, we briefly summarize the main points and focus our attention on the estimation of the probability at each node. In fact, at each node of BET, an estimate of the probability for the event at that node must be provided. In this way, the probabilities along any path in the tree will allow calculating the probability of the terminal event through the use of classical probability theorems (cf. Aspinall et al., 2003). It is important to stress that, by means of the BET structure, we can take into account all the possible events, and provide a probability estimate for their occurrence.

Different volcanoes have different behaviors and give rise to different types of event. BET allows this aspect to be considered, and the branching of BET depends on the behavior of the volcano itself, both in the structure and in the probability value at each node. For example, BET relative to Stromboli volcano must take into account the probability estimate for a tsunami due to its flank collapse, while for Mount Vesuvius we are not planning to evaluate such probability (considered negligible). In other words, the structure of BET is strictly linked to the eruptive activity of the volcano, to the geographic location of the volcanic system and to the degree of urbanization. For the sake of example, the sketch of a suitable BET for Mount Vesuvius is shown in Figure 9, and it is the one we will refer to.

In Figure 9, the different nodes (corresponding to different columns) have the following meanings:

- **Node 1**: there is an unrest, or not, in the time interval \((t_0 - \tau, t_0 + \tau)\), where \(t_0\) is the present time, and \(\tau\) is the time window considered.
- **Node 2**: the unrest is due to magma, or to other causes (e.g., hydrothermal, tectonics, etc.), given unrest is detected.
- **Node 3**: the magma will reach the surface (i.e., it will erupt), or not, in the time interval \((t_0 - \tau, t_0 + \tau)\), provided that the unrest has a magmatic origin.
- **Node 4**: the eruption will occur in a specific location, provided that there is an eruption.
- **Node 5**: the eruption will be of a certain “size/type” (e.g., VEI), provided that there is an eruption in a certain location.
- **Node 6**: a specific hazardous phenomenon is generated, given that an eruption of a specific size or type occurs.
- **Node 7**: a specific area around the volcano is reached by a particular hazardous phenomenon, given that an eruption of a specific size occurs in a vent location, and generates the hazardous phenomenon.
- **Node 8**: a specific threshold for a specific phenomenon is overcome, given the area is reached by the hazardous phenomenon accompanying the eruption of a specific size or type, occurring in a vent location.
The BET scheme reported above represents only the ‘hazard part’. The implementation to a risk assessment is straightforward because it requires the addition of two further branches, the exposed values (node 9), and the vulnerability (node 10).

Note that the events at any given level of the tree need not be mutually exclusive or exhaustive.

Figure 9 highlights another very appealing feature of BET, that is, BET provides a powerful scheme able to integrate different studies aiming to improve the hazard/risk assessment. For instance, the so-called hazard maps of the effects of a well defined phenomenon based on some selected similar eruptions (e.g., Cioni et al., 2003) do not represent the ‘absolute’ magnitude of the hazard, but the hazard conditioned to the occurrence of a specific event (i.e., they represent the nodes 6-8). From Figure 9, we can see that the knowledge of the first 5 nodes allows defining quantitatively the probabilities of a volcanic eruption of any magnitude in a given time interval. Including the subsequent node, we have the hazards of single well defined phenomenon (the occurrence of a pyroclastic flow, tephra, lahars, etc.).

Hereinafter we will refer to ‘node $k$’ to indicate one of the possible state, event, or condition of the $k$-th step of the event tree. At each one of these nodes we attribute a probability function. Let us define $\theta_k$ as the probability of the conditional event $E$ (note that each event reported above is conditioned to the occurrence of other events at previous nodes); therefore, for each one of the nodes we define $[\theta_1^{(\text{unrest})}]$, $[\theta_2^{(\text{magma})}]$, $[\theta_3^{(\text{eruption})}]$, $[\theta_4^{(\text{vent})}]$, $[\theta_5^{(\text{size})}]$, $[\theta_6^{(\text{phenomenon})}]$, $[\theta_7^{(\text{reaching})}]$, $[\theta_8^{(\text{threshold})}]$, where the square brackets stand for a generic “probability density function (pdf)”. In other words, BET considers the conditional probability at each node as a random variable, therefore it estimates each probability through a pdf, not as a single value.

As described in the following, the use of these pdfs (characteristic of the Bayesian inference) allows BET estimating aleatory and epistemic uncertainties. Since the first three nodes have only two possible states that are mutually exclusive and exhaustive (for instance, unrest or not), we set, for the sake of simplicity, $[\theta_1^{(\text{unrest})}] = [\theta_1]$, $[\theta_2^{(\text{magma})}] = [\theta_2]$, $[\theta_3^{(\text{eruption})}] = [\theta_3]$.

Given all the pdfs at each node, BET combines them in order to obtain the absolute probability of each event at which we are interested in. For instance, the pdf of the probability to have an eruption of type $m$ in a the time interval $(t_0, t_0 + \tau]$ $j$-th vent location, i.e, $\Phi_1$, is

$$\Phi_1 = [\theta_1] [\theta_2] [\theta_3  [\theta_4^{(j)}] [\theta_5^{(m)}]$$

(3)

In other words, $\Phi_1$ is a quantitative measure of eruption forecasting. For a visualization of the procedure, see the upper two blocks of Figure 9.

The functional form of $\Phi_1$ is not determined analytically, but through a Monte Carlo simulation. In practice, we sample 1000 times each pdf, and we perform the calculation by using each sample. Therefore, we obtain 1000 values of $\Phi_1$ that are used to determine the functional form numerically. In this way, we propagate, in a proper way, both aleatory and epistemic uncertainties at all nodes, and we estimate best guess (i.e., the average) and errors (the standard deviation) of the absolute probability of any possible event.

To summarize, BET provides quantitative estimations of eruption forecasting and volcanic hazard (and risk) through the evaluation of the pdfs of the nodes, by accounting for any kind of available information.
Figure 9. Bayesian event tree for a typical volcano.
2.2.2. Conditioned probability density function at each node

Generally speaking, we have two broad classes of information that can be considered at each node: from monitoring (dataset $\mathcal{M}$) and all the other kinds of data/information (dataset $\mathcal{M}^\text{other}$). This subdivision is mainly due to the fact that, usually, these two types of information have different weights in different states of a volcano. During an episode of unrest, monitoring data may be the most relevant for forecasting purposes, while the same data do not carry relevant information during a quiet period, apart from telling that the volcano is at rest. At the same time, it is obvious that monitoring data contain fundamental information that must be used to quantify mid- to short-term volcanic hazard. For these reasons, we introduce these kinds of information through two different functions. At the generic $k$-th node, the pdf of the $j$-th event is

$$\theta_k^{(j)} = \gamma_k \theta_k^{(j)|\mathcal{M}} + (1-\gamma_k) \theta_k^{(j)|\mathcal{M}^\text{other}}$$

where $\gamma_k$ is a variable in the interval $[0,1]$. $\theta_k^{(j)|\mathcal{M}}$ and $\theta_k^{(j)|\mathcal{M}^\text{other}}$ have the same meaning as $\theta_k^{(j)}$, but they are defined by using only monitoring information and all the other kinds of information (non-monitoring, hereinafter), respectively. Since in our case, we are mostly interested in long-term assessment, we set $\gamma_k = 0$ for each node, therefore, $\theta_k^{(j)} = \theta_k^{(j)|\mathcal{M}^\text{other}}$.

Each $\theta_k^{(j)}$ is determined through Bayesian inference. Given a set of data $y$, we have:

$$\theta_k^{(j)} = [\theta_k^{(j)}|y] \mid \theta_k^{(j)} \mid \mathcal{M}$$

where the two terms in the right hand side of equation 5 represents the prior distribution and the likelihood. The prior distribution describes all our knowledge based only on theoretical models and/or beliefs. The likelihood is the sampling distribution, that is the probability distribution of observing the data $y$ given a specific probability of occurrence of the $j$-th event characterizing node $k$. The term on the left hand side is the posterior distribution that represents a sort of merging of the information contained in the prior and in the likelihood.

The choice of the functional form of the prior distribution and of the likelihood function represents the core of the Bayesian inference, and it requires some physical and statistical assumptions on the process.

**Prior distribution**

We model the prior distribution for the $j$-th event at the $k$-th node $\theta_k^{(j)|\text{prior}}$ with a Dirichlet distribution (Marzocchi et al., 2004; Gelman et al., 1995) that, for a generic multivariate mutually exclusive and exhaustive random variable $\theta=(\theta^{(1)},...,\theta^{(m)})$, reads

$$\theta = \frac{\Gamma(\alpha_j + \ldots + \alpha_j)}{\Gamma(\alpha_j) \ldots \Gamma(\alpha_m)} (\theta^{(1)})^{\alpha_1-1} \ldots (\theta^{(m)})^{\alpha_m-1}$$

$$= \text{Dirichlet}(\alpha_j, j=1,\ldots, m)$$

where $\alpha_j > 0$ and $\theta^{(1)}...,\theta^{(m)} > 0$.

Since the random variable is a probability, the Dirichlet distribution is particularly suitable being unimodal and with domain $[0,1]$ in each variate. The first two moments (mean and variance) of the distribution are

$$E[\theta^{(j)}] = \frac{\alpha_j}{\alpha_0}$$

and

$$V[\theta^{(j)}] = \frac{\alpha_0 \alpha_j - \alpha_j^2}{\alpha_0^2 (\alpha_0 + 1)}$$

where $\sum_{j=1}^m \alpha_j = \alpha_0$.


In this case, the probability distribution of the \( j \)-th event at node \( k \) is the marginal distribution of a Dirichlet distribution that is a Beta distribution. In fact, the univariate case of a Dirichlet is called Beta distribution. It represents the Dirichlet distribution for two mutually exclusive events (e.g., magma or not). For a generic random variable \( \theta \), Beta reads

\[
[\theta] = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha) \Gamma(\beta)} \theta^{\alpha-1} (1-\theta)^{\beta-1} = \text{Beta}(\alpha, \beta)
\]  

(9)

where \( \alpha, \beta > 0 \), and a sufficient condition to have a finite pdf is \( \alpha, \beta \geq 1 \) (e.g., Gelman et al., 1995). Note that in the previous formula can be derived from equation 6 with \( m=2 \), \( \alpha_1 = \alpha \), \( \alpha_2 = \beta \), \( \theta_1 = \theta \) and \( \theta_2 = 1-\theta \). Consequently, also mean and variance for a Beta can be obtained by using the same substitutions in equations 7 and 8.

The average of the Dirichlet and Beta distributions represents an estimation of the aleatory uncertainty, i.e., the intrinsic (and unavoidable) random variability due to the complexity of the process. The dispersion around the central value (i.e., the variance), instead, represents an estimation of the epistemic uncertainty, due to our limited knowledge of the process. In spite of the latter being neglected in past works, its estimation is very important for correct comparison between the probabilities of different hazards, and the confidence limits that are ascribed to them (cf. Gelman et al., 1995; Woo, 1999). Moreover, Marzocchi et al. (2004; 2006) have shown that, by accounting for the epistemic uncertainties, also central values are significantly affected.

Note that the choice of the Dirichlet (Beta) distribution is itself rather subjective, and in some case probabilities may be more appropriately characterized by other distributional forms. However, any possible bias introduced by this subjective choice is certainly less than by assuming an exact value for the probability, that is assuming a Dirac’s \( \delta \) distribution; actually, the latter is a much more subjective choice because it neglects the epistemic uncertainty. Further details on this choice can be found in Marzocchi et al. (2004; see also Figure 10).

![Figure 10. Different example of Beta distributions. Dashed line represents the Dirac distribution \([\theta] = \delta(\theta-0.33)\) that can be seen as a Beta distribution with infinity values for \( \alpha + \beta \). Solid line represents a Beta distribution with \( \alpha = 2 \) and \( \beta = 4 \). Dotted line represents a uniform distribution, that is a Beta distribution with \( \alpha = \beta = 1 \).](image-url)
The definition of the prior distribution consists of setting the Dirichlet (Beta) distribution by using a priori information. In general, theoretical models, a priori beliefs, and/or expert elicitation give estimation of the expected central value of the prior distribution that represents the ‘best guess’. The variance can be seen as a sort of ‘degree of confidence’ of our a priori information, i.e., an evaluation of the epistemic uncertainties.

Likelihood function
Using Bayes’ rule with a chosen probability model means that the past data at node \( k \) \((y_k)\) affect the posterior inference only through the function \([y|\theta^0]\) (see equation 5) that is called likelihood function. In the present case, we choose a multinomial distribution that generic multivariate mutually exclusive and exhaustive random variable \( \theta^0 = (\theta(1),...\theta(m)) \) reads

\[
[y|\theta^0] = Mu_m(y^{(1)},...,y^{(m)};\theta^0) = \left( \frac{\sum_{j=1}^{m} y^{(j)}}{y^{(1)}\ldots y^{(m)}} \right) \left( \theta^{(1)} \right)^{y^{(1)}} \ldots \left( \theta^{(m)} \right)^{y^{(m)}}
\]

where \( y^{(i)} \) represents the number of successes relative to the event labeled \( i \) with probability \( \theta^{(i)} \).

In our case, for the \( k \)-th node we have

\[
[y_k|\theta_k] = Mu_m(y_k^{(1)},...,y_k^{(m)};\theta_k)
\]

In analogy with the previous section, in case \( m = 2 \) a multinomial distribution becomes a binomial distribution; let \( y_k \) be the variable that counts the number of occurrence of an event in a dataset of \( n_k \) data (e.g., at node 2, the number of magmatic intrusions \( y_2 \) out of the number of recorded unrest episodes \( n_2 \)), then

\[
[y_k|\theta_k] = Bin(y_k, n_k; \theta) = \left( \binom{n_k}{y_k} \right) \left( \theta \right)^{y_k} \left( 1-\theta \right)^{n_k-y_k}
\]

Posterior distribution
The choice of the Dirichlet and Multinomial (Beta and Binomial in the univariate case) distributions simplifies the computation, because they are conjugate distributions (Gelman et al., 1995), i.e., a Dirichlet multiplied by a Multinomial is still a Dirichlet. Through Bayes theorem and adopting the results of the conjugate families, we obtain the following posterior distribution for \( \theta_k^{(i)} \)

\[
[\theta_k] = [\theta_k|y_k] = Di_m(j = 1,...,m)
\]

In analogy to what reported above, for a binomial distribution we have

\[
[\theta_k] = [\theta_k|y_k] = Beta(\alpha_k + y_k, \beta_k + n_k - y_k)
\]

2.2.3. Combining the nodes: the probabilistic volcanic hazard assessment. The example of the tephra fall hazard

After to have evaluated the probability distribution at each node of the Event Tree, we can combine them to obtain any probability we desire. For example, the annual probability \( (\pi) \) of Tephra Fall (TF) for a specific site will be

\[
[\pi] = 12 \sum_{VEI} [\theta_1][\theta_2][\theta_3^{(VEI)}][\theta_6^{(VEI)}][\theta_7^{(Site)}][\theta_8^{(Thickness)}]
\]
where the summation is for all VEI considered (3, 4, and 5+), and the factor of 12 transform the month probability (see node 1 and 3) into annual probability. We stress that this approximation holds when the probabilities are small as in the present case. The multiplication is performed through 1000 values randomly selected for each node. At the end, we have one distribution for each thickness chosen.

2.2.4. The volcanic risk

The BET scheme is straightforward procedure to pass from volcanic hazard to volcanic risk. As mentioned before, we just need to multiply the hazard obtained in the previous section by the vulnerability of the exposed values. To do that, it is necessary to have vulnerability of edifices for different kind of phenomena, and models to estimate the damages. This is available only for few municipalities, therefore a national volcanic risk is not yet available. The most complete risk analysis has been carried out for Vesuvius (see Neri et al., 2008).

2.3. Hydrogeological risks

2.3.1. Preface

Hydrogeological Risk Management practice within Europe varies widely, mainly because:

a) the entity of the hydrogeological risk is different in different countries;
b) the nature and quality of available data is not uniform;
c) social attitudes vary among countries.

Hydrogeological risk management has the following objectives:

− identifying and understanding the nature and extent of risks;
− understanding and addressing public perceptions of and reactions to risk;
− establishing goals and standards;
− establishing strategies and policies to achieve these goals;
− minimize the costs involved while ensuring that existing and future developments are not exposed to “unacceptable” risks;
− ensuring that developments do not increase the risks for the rest of the community.

Several documents have been produced on EU policies, mainly for flood risk management. A “best practice” document produced by a core group of EU Water Directors (Water Directors, 2003) echoes many themes of flood risk management. Floods are a natural phenomenon; flood strategy should cover the entire river basin; the paradigm must shift from defensive action to management of risks and living with floods; and there should be action, including trans-national efforts, to restore natural flood zones such as wetlands and floodplains. Although structural measures will remain important for protecting human health and safety, and valuable property and assets, defence can never be absolute, and mitigation and non-structural measures are often more sustainable solutions in the long term. Guidelines for flood risk management have been produced by HR Walligford (2004).

The different methodologies currently in use for the definition of the Flooding Risk and Landslide Risk, amply described in the context of the ARMONIA Research Project of the Sixth European Framework Program, are illustrated herein, in more details, with reference to the Italian situation.

2.3.2. Flooding risk

Definition of the Flooding Hazard (H)

The definition of the Flooding Risk starts from the estimate of the Flooding Hazard. The first step is the probabilistic estimate of the discharge with a given return period (T). In Italy the usual procedure is to use as reference return periods of 20-50 years, 100-200 years and 300-500 years.
The estimate of the discharge at different $T$ is usually performed using the results and procedure defined by the GNDCI (Gruppo Nazionale Difesa dalle Catastrofi Idrogeologiche – www.gndci.cnr.it) in the context of the VAPI (Evaluation of floods in Italy) project. VAPI proposes a statistical methodology capable to relate directly a given discharge value with a fixed reoccurrence time for most of the River Basins of the national territory.

The VAPI procedure estimates design value of the variable $X_T$ (it represents either the annual maximum of the rainfall intensity of a given duration for a given $T$ or the annual maximum of the discharge for a given $T$) by a probabilistic methodology.

It is calculated by the following expression:

$$X_T = K_T \mu(X)$$  \hspace{1cm} (16)

where:

- $K_T$ = probabilistic growth coefficient which is function of the return period ($T$).
- $\mu(X)$ = average of the probability distribution of $X$. It is strongly dependent upon the physiographic characteristics of the site and the involved river basin.

The coefficient of probabilistic growth is calculated by adopting a **Two Components Extreme Value (TCEV)** procedure (Rossi F. et al., 1984; Beran M.A.; Osking J.R.M.; Arnel N.W., 1986; Arnel N.W., Gabriele S., 1988). It assumes that the maximum annual events are the result of a mix of two distinct populations: the first producing the maximum ordinary events, more frequent but less intense, the second produces extraordinary maximum events, less frequent but often catastrophic. Considering the TCEV, the relation between $T$ and $K_T$ results in the following expression:

$$T = \frac{1}{1-F_k(K)} = \frac{1}{1-\exp(-\Lambda_1 e^{\eta K} - \Lambda_2 \Lambda_1^{10/\eta} e^{\eta K/\theta} \Lambda_3)}$$  \hspace{1cm} (17)

The different parameters of the TCEV are evaluated by a procedure of hierarchical regionalization. In fact, they are evaluated at different regional scales. In particular, parameters of higher statistical order (shape and scale) are analyzed in larger regions that are assumed homogeneous with respect to them. Contrarily to $K_T$, $\mu(X)$ varies largely from site to site. This variability is assumed as the result of random factors.

When equation 16 is used to calculate the annual maximum of rainfall intensity of a given duration for a given $T$, the VAPI procedure identifies different homogeneous rainfall areas, each of them having constant known parameters of the law of rainfall probability.

When equation 16 is used to estimate the annual maximum of discharge for a given $T$, the VAPI procedure uses either an empiric correlation analysis, among the main climatic, geomorphologic, hydrogeologic and land use factors of the river basin or two different conceptual models, one based on **rational formula** (Chow, V.T. et al., 1988), and the other based on a **geomorphoclimatic model** (Rossi F., Villani P., 1988).

Once the discharge has been evaluated in a given section for a given return period, the second step is the definition of the wet areas. Usually this is done through a steady flow analysis for defining the boundaries of the wet areas between a couple of cross sections (Ponce V.M., Simons D.B., Li R. 1978; Todini E., Bossi A., 1986; Franchini M., Todini E., 1989). More sophisticated methods employ one- or two-dimensional unsteady flow analysis (Yen M., 1973; Fraccarollo L., Toro E.F., 1995; Jin M., Fread, D.L., 1997; Brufau P., Garcia Navarro, 2000; Hubbard M.E. 2001; Caleffi V., Valiani A., Zanni A., 2002). The output of the hydraulic models includes hydraulic depth, velocity and dwell time.

Generally three wet areas are defined, corresponding to three different return periods, i.e. to three different flooding hazards:

1. Areas with high probability of flooding ($T = 20 - 50$ years);
2. Areas with moderate probability of flooding ($T = 100 - 200$ years);
3. Areas with low probability of flooding ($T = 300 - 500$ years).
Definition of damage (D)
The assessment of the expected damage is performed identifying the elements at risk and its value (E) first, and then estimating its vulnerability (V). Elements at risk are essentially man-made structures, land and people. The damage assessment is performed considering hydraulic depth, dwell time and velocity. Hydraulic depth and dwell time are always used for estimating the static flooding damage. Velocity is considered to estimate damages to manufacts produced by flood waves’ impact. The impact (Pt) of the flow against a manufact is defined as a function of the dynamic pressure p and of hydraulic depth h:

\[ Pt = p \cdot h = \frac{1}{2} d \cdot v^2 \cdot h \]  

(18)

The analysis of vulnerability of building is carried out taking into consideration not only the different structure typologies, but also the different types of windowing in the exposed walls, for their effect on the mechanical resistance. Land use is the main considered parameter to estimate vulnerability of agricultural, pasture and forest zones. Different criteria are used to estimate damage level for different river basins in Italy.

Definition of the flooding risk
The Flooding Risk R is defined as the product of three factors:

\[ R = H \cdot V \cdot E = H \cdot D \]  

(19)

Generally boundaries of Flooding Risk prone areas are defined according to different risk levels. The latter are estimated by using probability matrixes that allow for the combination of flooding hazard, with information on the damage induced by a given flooding level in a given area. Four indicative risk levels are defined:
- Moderate (R1): social, economic and environmental damages are marginal;
- Medium (R2): minor damages to buildings, infrastructures and environment are possible. No significant effect on people, functionality of buildings and economic activities;
- High (R3): concern exists on peoples’ safety. Functional damages to buildings and infrastructures are possible as well as interruption of the economic activities and relevant damages to the environment;
- Very High (R4): expected damages include casualties and injuries, serious damages to buildings and infrastructures, destruction of the environment and of the socio-economic activities.

2.3.3. Landslide risk

Definition of the landslide hazard (H)
The first step in the evaluation of Landslide Hazard is the definition of the triggering susceptibility. This is performed using various methodologies, including (Soeters and Van Westen, 1996; Van Westen et al., 1997; Aleotti and Chowdhury, 1999):
- landslides inventory maps;
- heuristic methods;
- deterministic physical methods;
- statistical methods.

Landslides inventory maps are compiled mainly using photo-interpretations merged with historical data. They report information about the landslide type and its dynamics (Guida et al., 1978). The space density of landslide events is represented through isoplethes (lines at equal percentage of landslide areas) as well as the percentage of landslide prone areas for each geological unit (Brabb et al., 1972; Radbruch-Hall, 1982).
Heuristic methods allow for the evaluation of triggering susceptibility associating weights to the various instability factors affecting a given slope. The final map is obtained by superposition of the thematic maps (Anbalagan, 1992; Turrini et al., 1998; Turrini and Visintainer, 1998). The deterministic physical based method is based on the calculation of the safety factor of the slopes through the analysis of stability of the limit equilibrium. This approach has been widely adopted in civil engineering and applied in geology after the introduction of the GIS (Terlien et al., 1995; Wu & Sidle, 1995). Among the most utilized we cite the models of Shalstab of Montgomery and Dietrich (1994) and the SINMAP (Pack et al., 1998).

Statistical analysis is often utilized for probability assessment on a basin scale. This analysis involves comparison of an inventory of observed landslides with the distribution of physical factors causing landslides either directly or indirectly. The obtained results can be extrapolated to landslide prone areas with no active mass movements, where potential instability conditions occur (Brabb, 1984; Yin and Yan, 1988; Van Westen, 1993; Carrara et al., 1995; Chung et al., 1995).

By using any of the models previously described, one can obtain an evaluation of the susceptibility to landslide of specific areas, but most of all, can obtain a classification of the territory of interest in different classes of landslide susceptibility.

The second step is the definition of the areas prone to be invaded by each landslide of a given triggering susceptibility level.

The typology of landslides differs according to rock types forming the slopes: for example, fast-moving landslides (mud-debris flows) are typical of volcanic loose pyroclastic deposits, slow-moving landslides are observed frequently in flysch deposits. Collapses and rock falls are typical of carbonate rocks.

A classification of the territory of interest into different classes of invasion susceptibility is done, but the definition of such areas, differently than in the preceding step, is based on different methodologies according to the different types of landslide considered.

In the case of fast-moving landslides, like mudflows, the delimitation of the areas potentially at risk of invasion is often done using the reach angle (Scheidegger, 1973; Hsü, 1975; Corominas, 1997; Legros, 2002). The reach angle is the angle from the horizontal of the line connecting the highest point of the landslide crown scarp to the distal margin of the displaced mass.

![Diagram of Reach angle](image)

**Figure II. Definition of Reach angle (H is topographic elevation, L the horizontal distance).**

Results of hazard estimates must provide the following parameters:
- maximum height of triggering;
- height of break of slope;
- height of expected invaded area;
- expected invaded area;
- thickness of displaced rock;
- volume of displaced rock;
- width of the landslide front.

In the case of slow-moving landslides, typical of flysch deposits, the delimitation of triggering susceptibility areas coincides with the invasion susceptibility areas, given the slow dynamics of the landslide motion.

In the case of rockfalls, one of the most difficult variables to calculate for the delimitation of the areas susceptible to rockfall is the reference “volume” of rock that will be displaced, which is an index of the intensity of the expected event. It is generally estimated through field observations and historical data. The fall trajectory of the rocks and their arrest points along the slope are calculated applying specific computational softwares and accounting for the real topographic profile.

By connecting the areas at the same level of triggering and invasion susceptibility, the landslide hazard level is determined for the area under analysis. Normally, four levels of landslide hazard are described:
- low hazard;
- medium hazard;
- high hazard;
- very high hazard.

**Definition of the damage (D)**

The evaluation of the damage induced by potential landslide events is performed in the same way already described for floods.

In the case of landslide events, the definition of the criteria followed to define damage levels is strictly dependent upon the type of landslide.

**Fast moving landslides (e.g. pyroclastic material)**

The definition of the damage produced by fast moving landslides is based mainly on the information about the intensity of the event itself based on the outputs of the hazard studies. Damages are estimated using the same procedures described for floods.

**Slow landslides (i.e. flysch)**

In the specific case of slow landslides, the velocity of displacement may be as low as a few centimeters per day. The area affected by the displacement is often very large and the phenomenon can last even months or years. The final displacement can also reach tens of meters.

To define the damage scenarios, manufacts in the areas potentially susceptible to sliding and in the areas that are invaded by it must be identified.

The buildings in the area can be greatly dislocated because of the translation of the bottom layer. The translation can occur both in the vertical and in the horizontal plane.

Slow land displacement is rarely uniform in space, even at a small scale, and time. For this reason, buildings are subject to differential collapse, both horizontal and vertical. In light of these considerations, it is assumed that all buildings present on the affected areas are subject to damages that make them inhabitable. Analogously, the exposed road sections are considered to be interrupted. Due to the low velocity of the motion, crops are generally considered to be unaffected or slightly damaged.

**Rockfalls**

Rockfalls generally affect relatively small areas, since the displaced mass is normally formed by rolling lithic rocks. Localized impacts by high density rocks are the most likely phenomenon occurring in these cases. Landslides can occur as a rock detachment from nearly vertical walls. In this case, buildings located close to the landslide triggering point may be hit from above suffering a dynamic concentrated load of very high intensity. In many cases the suffered damages are such to inhibit habitability and threat people safety. Other buildings still within the run-out zone but further away from the rockslide front can be hit by single rolling rocks. Hence the expected damage is very high close to the landslide triggering area and decreases rapidly with increasing distance.
The probability of interruption of exposed road sections is estimated with the same principles. Crops are in general expected to sustain severe to very severe damage in the areas proximal to the landslide triggering zone.

**Definition of the landslide risk (R)**

As Flooding Risk, boundaries of Landslide Risk prone areas are defined according to different risk levels. The latter are estimated by using probability matrices that allow for the combination of flooding hazard, with information on the damage induced by a given invasion level in a given area.

Also in this case four indicative risk levels are defined:
- moderate (R1): social, economic and environmental damages are marginal;
- medium (R2): minor damages to buildings, infrastructures and environment are possible. No significant effect on people, functionality of buildings and economic activities;
- high (R3): concern exists on peoples’ safety. Functional damages to buildings and infrastructures are possible as well as interruption of the economic activities and relevant damages to the environment;
- very high (R4): expected damages include casualties and injuries, serious damages to buildings and infrastructures, destruction of the environment and of the socio-economic activities.

### 2.4. Industrial risks

#### 2.4.1. Methodology

The methodology used in industrial risk quantification first requires the definition of one or several risk scenarios. This allows to define the information required to assess the risk, reducing the infinite possible combinations of sources, adverse events and expected damages to those that are actually possible. Such information must be both qualitative and quantitative. It must include risk sources and the related adverse events, the phenomena produced by the adverse event, and even the specific meteorological conditions and the presence of people at risk in certain areas. They are gathered in “classes” which, from a logic point of view, coincide with the branches of an Event Tree. The Event Tree is of course an instrument and not a method, or rather it is one of the possible ways to represent a risk scenario. Similar events can be gathered in classes and each class can be graphically represented as a branch of the Event Tree and quantified thanks to a probability conditioned by the occurrence of events of other classes. The definitions of these classes, to be associated to an occurrence probability, are the following:

- $\theta_s$: Hazardous substance release from an industrial plant within a given time interval (loss of containment).
- $\theta_{s,i}$: Type of substance released because of the loss of containment.
- $\theta_{c}$: Source of the release.
- $\theta_{c,i}$: Released amount (Released Amount Index, RAI), of a specific substance from a certain source. The RAI provides a measure of the amount released and represents the incident.
- $\theta_{c,i}^{(e)}$: Phenomenon generated by the event under the form of toxic release, explosion or fire according to the toxicity and/or inflammability characteristics of the substance, given the occurrence of a specific event in the preceding node. This index represents the incident outcome.
- $\theta_{c,i}^{(f)}$: The spatial distribution of the phenomena generated by the adverse event. This is correlated to the meteorological conditions.
- $\theta_{c,i}^{(g)}$: Intensity distribution of the phenomenon in a downwind area where the consequences have to be analysed (chosen as reference damage), given the occurrence of a specific incidental event. It is strongly influenced by the local atmospheric conditions (classes of atmospheric stability and wind rose). This index represents the incident outcome case.
- $\theta_{c,i}^{(h)}$: Presence of people in the selected area.
- $\theta_{c,i}^{(i)}$: Induced lethality.
When the events occur, the following probabilities will be associated to each of the classes $P(\theta_{j,i})$:

- $P(\theta_{A,i})$ Probability that a hazardous substance release from the industrial plant occurs in a given time interval.
- $P(\theta_{B,i})$ Probability of release of a specific substance.
- $P(\theta_{C,i})$ Probability that the release comes from a specific source.
- $P(\theta_{D,i})$ Probability that a certain amount is released (RAI).
- $P(\theta_{E,i})$ Probability that the event occurs under the form of a specific phenomenon (toxic release, explosion or fire).
- $P(\theta_{F,i})$ Probability that a specific phenomenon goes toward a specific direction.
- $P(\theta_{G,i})$ Probability that the phenomenon has a certain intensity distribution in an area where the consequences are to be investigated.
- $P(\theta_{H,i})$ Probability of the presence of people where the phenomenon occurs.
- $P(\theta_{I,i})$ Probability of death of people in the area, due to the exposure to the phenomena generated by the event.

As stated above, a branch of the Event Tree, built on the basis of a risk scenario, can be associated to the probabilities of each event, phenomenon or consequence of the selected classes. The risk scenario identifies the top event, that is the event originated by a selected risk source, triggering the subsequent events. An example of a scenario, under the form of a table summarizing the information needed to quantify the risk related to the occurrence of a certain number of conditions, is the following (Table 6):

<table>
<thead>
<tr>
<th>Risk source</th>
<th>Tanks under pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adverse event</td>
<td>Release of an inflammable substance</td>
</tr>
<tr>
<td>Possible Phenomena</td>
<td>Toxic cloud. Pool. Fire. Explosion</td>
</tr>
<tr>
<td>External exposure path</td>
<td>Air. Soil. Subsoil. Layer. Surface water</td>
</tr>
<tr>
<td>Internal exposure</td>
<td>Inhalation. Ingestion. Dermic contact</td>
</tr>
<tr>
<td>Target</td>
<td>PAR. Infrastructures</td>
</tr>
<tr>
<td>Damage</td>
<td>Death (direct or indirect)</td>
</tr>
</tbody>
</table>

An Event Tree, where these branches can be easily identified, is shown in Figure 12. It shows clearly and orders logically the elements selected for the “release of inflammable substance (GPL) from tanks under pressure” risk scenario.
Figure 12. Representation of a generic event tree reporting the probability that the event related to each sector occurs.
2.5. Industrial risk assessment: the case of LPG storage

2.5.1. Description of the case study and of the selected plant

The industrial plant selected for the risk index assessment is an LPG storage plant. In this plant the liquefied gas is transported in pipelines through a pipebridge that draws the LPG from underground tanks. It is therefore possible to identify different risk sources. Risk source means any equipment, pipeline or reactor that can cause an adverse event.

A number of areas can be identified in the storage plant. In each area, there are different risk sources:
1. **Zone of storage in tanks** where six 200 m³ horizontal cylindrical tanks receive the LPG directly from the pipebridge; the temperature and the pressure of storage are respectively 25°C and 8.5 bar.
2. **Tanker loading zone** where five tankers are directly filled from the pipebridge; the temperature and the pressure of storage are respectively 20°C and 8.35 bar.
3. **Bottling area** where there are two bottling installations for the filling of cylinders of 100 kg capacity; the temperature and the pressure of storage are respectively 20°C and 8.35 bar.
4. **Cylinder park** where a maximum of 8000 cylinders can be stocked; the temperature and the pressure of storage are respectively 20°C and 8.35 bar.
5. **Pumps and compressors zone**, in which there are two compressors (T = 60°C, P = 8.5 bar) and two pumps (T = 20°C, P = 29 bar) pumping the LPG from the tanks to the cylinder filling zone.
6. **Area covered by the pipebridge**. The area is crossed by a pipebridge with 0.16 m section, length 800 m at a height of 10 m from the ground. The temperature and the pressure within the pipebridge are respectively 25°C and 8.5 bar.

2.5.2. Assessment of incidents, occurrence frequency and damage

To carry out the identification and the gathering of the risk source it is necessary to identify the equipment of a specific production line that can be considered similar. This means that the identified equipment must have the same function, the same potential consequences and the same probability of generating the same adverse event. Each equipment is associated with an occurrence frequency of the adverse event and the extent of the consequences due to the event itself is assessed. To take into account the simultaneous presence of N equal equipment, the frequency associated to a single equipment has to be multiplied by the number N of similar equipment.

**Zone of storage in tanks**

The storage pressure of LPG is higher than 1 bar. Therefore it is necessary to identify the incidents that are distinctive for pressurized tanks:
1. R₁ₜ Sudden release of the whole contents of the tank (d = 50 mm).
2. R₂ₜ 10 minutes continuous release of the whole contents of the tank (it is therefore necessary to identify the equivalent diameter of a cracking that can lead to a complete emptying of a 200 m³ tank in 10 minutes).
3. r₁ₜ 10 minutes steady and continuous release from a 10 mm equivalent diameter cracking.

The event R₁ₜ and the event R₂ₜ can be defined “catastrophic” and are borderline cases. The occurrence frequency of the events R₁ₜ, R₂ₜ or r₁ₜ and the value of the released amount are listed in Table 7.

The tanks are downstream connected to the collector through pipelines (5 meters of length). Two incidents can be identified:
1. R₁ₚ Catastrophic breaking of the pipeline (100 mm in the case in question: outflow from both the sides of the broken pipeline).
2. r₂ₚ Cracking: release from a cracking with a diameter equal to 10% of the pipeline diameter as a maximum (10 mm in the case in question). It is valid for 50 mm cracking as a maximum.
Table 7. Occurrence frequency of released amount for the events $R_{i1t}$ and $R_{i2t}$, $r_{i1t}$.

<table>
<thead>
<tr>
<th>Incident</th>
<th>$R_{i1t}$</th>
<th>$R_{i2t}$</th>
<th>$r_{i1t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (occ/y)</td>
<td>$3 \times 10^{-6}$</td>
<td>$3 \times 10^{-6}$</td>
<td>$6 \times 10^{-5}$</td>
</tr>
<tr>
<td>Released amount (kg)</td>
<td>70793</td>
<td>70793</td>
<td>838</td>
</tr>
<tr>
<td>RAI</td>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 8. Occurrence frequency of released amount for the events $R_{ip}$ and $r_{2p}$.

<table>
<thead>
<tr>
<th>Incident</th>
<th>$R_{ip}$</th>
<th>$r_{2p}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (occ/y)</td>
<td>$3.15 \times 10^{-6}$</td>
<td>$2.39 \times 10^{-5}$</td>
</tr>
<tr>
<td>Released amount (kg)</td>
<td>33400</td>
<td>337</td>
</tr>
<tr>
<td>RAI</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

**Tanker loading zone**

Also in this case, the pressurization of the tankers has to be considered. The following incidents can be identified for the tankers:

1. $R_{i1t}$. Sudden release of the whole amount of LPG (catastrophic broken).
2. $R_{2t}$. Continuous release due to the complete breaking of the major connection.
3. $r_{1t}$. Complete broken of the loading-unloading arm (ID = 76 mm). Outflow from both the sides.
4. $r_{2t}$. Cracking of the loading-unloading arm: the release comes from a cracking having a diameter equal to 10% of the diameter of the hose as a maximum (7.6 mm for the case in question). It is valid for cracking of 50 mm as a maximum.

Table 9. Occurrence frequency of released amount for the events $R_{i1t}$, $R_{2t}$, $r_{1t}$ and $r_{2t}$.

<table>
<thead>
<tr>
<th>Incident</th>
<th>$R_{i1t}$</th>
<th>$R_{2t}$</th>
<th>$r_{1t}$</th>
<th>$r_{2t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (occ/y)</td>
<td>$6.25 \times 10^{-7}$</td>
<td>$6.25 \times 10^{-7}$</td>
<td>$5.4 \times 10^{-4}$</td>
<td>$5.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>Released amount (kg)</td>
<td>20198</td>
<td>20198</td>
<td>19300</td>
<td>195</td>
</tr>
<tr>
<td>RAI</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

**Bottling area**

In this area, where the cylinders are filled and handled, the following incidents can be considered:

1. $R_{i1b}$. Sudden release of the whole amount of LPG.
2. $r_{1b}$. Complete broken of the loading-unloading hose (ID = 12 mm). Outflow from both the sides.
3. $r_{1b}$. Cracking of the loading-unloading hose: the release comes from a cracking having a diameter equal to 10% of the diameter of the hose as a maximum (1.2 mm for the case in question). It is valid for cracking of 50 mm as a maximum.

Table 10. Occurrence frequency of released amount for the events $R_{i1b}$, $r_{1b}$ and $r_{1b}$.

<table>
<thead>
<tr>
<th>Incident</th>
<th>$R_{i1b}$</th>
<th>$r_{1b}$</th>
<th>$r_{1b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (occ/y)</td>
<td>$5 \times 10^{-3}$</td>
<td>$4.4 \times 10^{-4}$</td>
<td>$4.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>Released amount (kg)</td>
<td>100</td>
<td>100</td>
<td>4.84</td>
</tr>
<tr>
<td>RAI</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>
**Cylinders park**

In this area the following incidents can be identified:

1. \( R_{1c} \) Catastrophic breaking of the cylinder.
2. \( R_{2c} \) Cracking: allowing the complete outflow of the cylinder’s contents.

<table>
<thead>
<tr>
<th>Incident</th>
<th>( R_{1c} )</th>
<th>( R_{2c} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (occ/y)</td>
<td>( 8 \times 10^{-3} )</td>
<td>( 8 \times 10^{-2} )</td>
</tr>
<tr>
<td>Released amount (kg)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>RAI</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

**Pumps and compressors zone**

The following incidents can be identified for both the pumps and the compressors:

- \( R_{1p/c} \) Catastrophic breaking of the major pipeline (diameter of 76 mm for the case in question) connected to the pump and the compressor.
- \( R_{2p/c} \) The release comes from a cracking with a diameter equal to 10% (as a maximum) of the diameter of the major pipe linked to the pump or to the compressor (7.6 mm for the case in question). It is valid for cracking of 50 mm as a maximum.

For conservative reasons, pumps and compressors not equipped with special security devices are considered.

<table>
<thead>
<tr>
<th>Incident</th>
<th>( R_{1p/c} )</th>
<th>( R_{2p/c} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (occ/y)</td>
<td>( 2 \times 10^{-4} )</td>
<td>( 1 \times 10^{-3} )</td>
</tr>
<tr>
<td>Released amount (kg)</td>
<td>34297</td>
<td>346</td>
</tr>
<tr>
<td>RAI</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

**Area covered by the pipebridge**

The following incidents can be identified for the pipebridge:

- \( R_{1pb} \) Catastrophic breaking of the pipebridge (160 mm for the case in question): the outflow comes from both the sides of the broken pipebridge.
- \( r_{2pb} \) Cracking: the release comes from a crack with a diameter equal to 10% of the diameter of the pipebridge (16 mm for the case in question).

<table>
<thead>
<tr>
<th>Incident</th>
<th>( R_{1pb} )</th>
<th>( r_{2pb} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (occ/y)</td>
<td>( 2.09 \times 10^{-4} )</td>
<td>( 1.47 \times 10^{-3} )</td>
</tr>
<tr>
<td>Released amount (kg)</td>
<td>70207</td>
<td>702</td>
</tr>
<tr>
<td>RAI</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

**Probability assessment of the classes of events**

Paragraph 1.2.2. shows that the occurrence frequencies of the incidents can be directly obtained from the literature. In other words, from the databases it is possible to directly deduce the occurrence probability corresponding to the product of the probabilities of the first four branches of the Event Tree:
\[ P_{\text{INCIDENT}} = \prod_{j=A}^{D} \theta_j \]  

(20)

For instance, if the probability of LPG release from a pipeline with an intensity \( RAI = 4 \) is considered, such probability is equal to the sum of the probabilities of all the possible release events with intensity \( RAI = 4 \) that can occur on pipelines bringing LPG within the plant.

In the case in question, the probability is given by:

\[ P_{\text{INCIDENT,RAI = 4}} = 6P(R_{ip}) = 1.89 \times 10^{-5} \]  

(21)

\( P(\theta_E) \). **Probability that a release of LPG from a well-defined source with a certain RAI intensity can cause a certain incident outcome**

Once the release from a well-defined source (pipe) has occurred with a fixed intensity \( RAI = 4 \), it is necessary to identify which incident scenarios (incident outcomes) might happen. Being the substance flammable and non-toxic, only the probabilities related to the phenomena of fire and explosion have to be considered. Since the considered release comes from a pipeline and not from a tank, fireballs or bleves cannot occur. Although the stored substance is in liquid phase, the conditions are such as to generate a biphasic outflow, with a negligible liquid phase. For this reason, the formation of a pool with consequent generation of poolfire can be excluded. The incident outcomes to be considered are thus the jet fire (event \( \theta_{E,4} \)), the flash fire (event \( \theta_{E,7} \)) and the VCE (event \( \theta_{E,8} \)). The first event occurs in case of immediate trigger, while the second and the third event occur in case of delayed trigger. The occurrence probability of an immediate trigger is \( P_{ii} = 0.065 \) therefore corresponding also to the probability of a jet fire occurrence. The complementary probability \( P = 0.935 \) is associated to the opposite event, represented by the non-immediate trigger. This latter event is made of two events, the delayed trigger and the non-trigger, to which are respectively associated, within the immediate non-trigger event, the two following probabilities, complementary between themselves, \( P_{ir} = 0.9 \) and \( P_{ni} = 0.1 \).

Within the retarded trigger it is necessary to distinguish between the probability of generating a flash fire \( (P = 0.6) \) and the probability of generating a VCE \( (P = 0.4) \).

On the basis of these data, a small Event Tree, related only to the E Class, can be built:

As an example, it was chosen to consider the probability that the \( \theta_{E,4} \) event, belonging to the E Class (that is the jet fire) occurs. The following probability is associated with it:

\[ P(\theta_{E,4}^{ii}) = 0.065 \]  

(22)
\( P(\theta) \). **Probability that a release of LPG by a well-defined source with a certain RAI intensity causes a specific incident outcome along a given atmospheric sector**

Once the incident outcome has been identified, the probability that the wind blows in a given direction has to be identified. Such probability can be deduced using the meteorological data related to the considered area. If a total number of 8 sections is chosen, for the sake of simplicity, in absence of the data, the searched probability may be considered:

\[
P(\theta_{inc}) = 0.125
\]  

(23)

\( P(\theta) \). **Probability that the effects due to the examined incident outcome are distributed with a certain intensity along a downwind direction downstream of the source (incident outcome case)**

In the case in question, the intensity distribution of the thermal flow has to be studied. Such distribution depends on the stability class taken into account. Thus the probability associative to this event is represented precisely by the probability that there is a specific class of atmospheric stability associated to a specific speed of the wind.

All the possible combinations of classes of stability and direction of winds can be gathered in the following 5 categories to which it is possible to associate a probability depending on the meteorological data of the examined area: B3-D5-D1-D2-F2.

The damage thresholds that can be associated to the thermal flow are the following (Table 14):

<table>
<thead>
<tr>
<th>Damage threshold</th>
<th>Sure mortality</th>
<th>High mortality</th>
<th>Beginning mortality</th>
<th>Irreversible injury</th>
<th>Reversible injury</th>
<th>Damage absence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal flow</td>
<td>37 kW/m²</td>
<td>12.5 kW/m²</td>
<td>7 kW/m²</td>
<td>5 kW/m²</td>
<td>3 kW/m²</td>
<td>1.4 kW/m²</td>
</tr>
</tbody>
</table>

For each atmospheric stability class, it is possible to identify the downwind points where the various thresholds are reached.

If the F2 class is considered, this being the class that typically occurs during the night, for the sake of simplicity, a probability of 0.5 is associative to it.

The following distribution of thermal flow, depending on the distance from the source, is obtained (Table 15):

<table>
<thead>
<tr>
<th>I (kW/m²)</th>
<th>Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>22</td>
</tr>
<tr>
<td>12.5</td>
<td>55</td>
</tr>
<tr>
<td>7</td>
<td>76</td>
</tr>
<tr>
<td>5</td>
<td>91</td>
</tr>
<tr>
<td>3</td>
<td>117</td>
</tr>
<tr>
<td>1.4</td>
<td>169</td>
</tr>
</tbody>
</table>

Thus, the effects of the jet fire exhaust within a distance of 170 m.
To give an example, if the event $\theta_{G,5}$ is considered, that is the event of having a thermal flow at $I = 3\, kW/m^2$ at $117\, m$ from the source, the probability that this occurs is given precisely by the probability that an F2 stability class is actually occurring:

$$P(\theta_{G,5}^\text{F2}) = P(F2) = 0.5 \quad (24)$$

$P(\theta_{H})$. Probability that there are people in the considered damaged area, occupied by a given category of population

The storing system in question is located in an industrial area. It is therefore possible to hypothesize that the population is constituted exclusively by workers (event $\theta_{H,2}$). The probability that a worker is exposed to the effects of an incident outcome can be calculated considering a working shift of 8 hours out of 24 daily hours, 5 days out of 7, 11 months out of 12:

$$P(\theta_{H,2}^\text{F2}) = 0.218 \quad (25)$$

$P(\theta)$. Probability of casualties induced by the intensity of the event in the selected damaged area identified

It is possible to associate a probability of death to the different thresholds considered for the event, by using the probit function.

In the following table are shown the probabilities of death associated to the different distances chosen within the considered interval for the event $\theta_{G,i}$ (Table 16):

<table>
<thead>
<tr>
<th>Thermal flow I (kW/m$^2$)</th>
<th>Distance (m)</th>
<th>Death probability</th>
<th>Individual Risk for Category of person</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>22</td>
<td>1</td>
<td>$1.70 \times 10^{-8}$</td>
</tr>
<tr>
<td>12.5</td>
<td>55</td>
<td>1</td>
<td>$1.70 \times 10^{-8}$</td>
</tr>
<tr>
<td>7</td>
<td>76</td>
<td>0.999</td>
<td>$1.69 \times 10^{-8}$</td>
</tr>
<tr>
<td>5</td>
<td>91</td>
<td>0.975</td>
<td>$1.65 \times 10^{-8}$</td>
</tr>
<tr>
<td>3</td>
<td>117</td>
<td>0.53</td>
<td>$0.89 \times 10^{-8}$</td>
</tr>
<tr>
<td>1.4</td>
<td>169</td>
<td>0.01</td>
<td>$1.70 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

It follows that in the considered area of damage, the probability of death will have a distribution between 1 and 0.01.

The individual risk index can be calculated as the product of the probabilities associated to each branch of the Event Tree:

$$ir_i = \prod_{j=A}^{I} \theta_{ij} \quad (26)$$

And from here:

$$1.68 \times 10^{-8} < ir_i < 1.68 \times 10^{-10} \quad (27)$$
If the individual risk associated with a well-defined point in the area is to be determined, it is possible to associate to this point a well-defined probability of death. For example, if a point located at 117 m from the source in downwind direction is considered, the following index of individual risk will be associated:

\[ i_r = \frac{8.92 \times 10^{-7}}{} \] (28)

2.6. Environment contamination risks

2.6.1. Methodology

The quantification of the contamination risk may be outlined in three main steps:

a. characterization of the contaminants release;

b. estimation of the substances migration in different environmental matrixes

c. estimation of the damage due to the internal exposure to contaminating substances.

For each of the abovementioned steps, inputs data may be obtained by on-site analysis, monitoring and mathematic models. A preliminary step for quantification of the contamination risk is the designing of a “conceptual site model” that is a typical tool of the environmental risk assessment and, in practice, coincides with the general definition of “risk scenario” that has been previously given in the Part I.

Input data and information necessary to quantify the site model may be distinguished in:

- inputs not changing in time and space (i.e digging’s dimensions, hollow’s depth) (marked by “N”);
- inputs changing in time and space (each hydro-geologic parameters) (marked by “V”).

The most significant parameters and variables that must be included in the scenario/site model in the specific case of a landfill (where contamination is due to leachate release in the soil and sub-soil and biogas dispersed in the ambient air) are the following ones:

- **geometric features**: area, dug-out area depth and volume;
- **operational modalities**: filling, compaction/compression and daily covering;
- **building features**: lateral sides’ bottom and final surface’ coating system;
- **coating systems properties**: thickness, density, hydraulic conductivity;
- **technological equipment features**: leachate collecting system, biogas captation system, biogas combustion torches, biogas energy recovery engines;
- **incoming waste typology**: streams/flows, products’ typology;
- **landfill wastes features**: bulk density, hydraulic conductivity, humidity content;
- **leachate composition**;
- **biogas’s composition**;
- **geologic formation information and description**;
- **existing water-bearing systems features and description**;
- **existing water-bearing systems identification and description**;
- **surface hydraulic bodies**;
- **identification of existing relationships between groundwater and surface water**;
- **meteorological data**: precipitations and winds;
- **groundwater features**;
- **potential receptors identification**: water-bearings, wells, watering;
- **surface employment**;
- **potential receptors identification**.

As reported for the industrial risk, the contamination risk estimation can be done by making some preliminary assumptions and by defining a set of groups. The following assumptions have been made in the reported case study.
1. the domino effect is ignored in order to consider possible events as independent one from the other;
2. human direct mortality is chosen as reference damage, ignoring damages to ecosystems and species’ loss;
3. only the direct exposure to potentially dangerous substances is considered, ignoring bio-accumulation or magnification;
4. short-term outcomes are considered.

Even in this type of risk the event tree is used as a tool to quantify the probability to have a death as a consequence of the daily intake of a specific contaminant that reaches the target throughout a specific external (migration) and internal (e.g. ingestion, inspiration and dermal contact) exposure pathways.

The groups involved in the risk scenario and included in the events tree are:
- \( \theta_A \) Release from a source
- \( \theta_B \) Type of the specific substance released by the source
- \( \theta_C \) Active pathways
- \( \theta_D \) Specific substance release from the source with a given entity in given geologic and hydro-geologic conditions
- \( \theta_E \) Contaminated environmental sectors considered as main contaminating source (namely the environmental sector suffering the contamination) and as second contaminating source (namely the environmental sector contaminated due to a contaminating substances migration)
- \( \theta_F \) Incident event outcome considered as the dispersion in the atmosphere, in the surface, in groundwater or surface water, of the contaminating substances. It depends on the chemical and physical properties of the released substance and the site-specific characteristics.
- \( \theta_G \) Incident event manifestation on the territory.
- \( \theta_H \) Phenomenon intensity distribution in an area surrounding the source
- \( \theta_I \) Direct exposure pathway.

The following \( P(\theta_j) \) probabilities must be associated to the latter groups:
- \( P(\theta_A) \) probability of an adverse event occurrence
- \( P(\theta_B) \) probability for the released substance to be potentially dangerous
- \( P(\theta_C) \) probability of geologic and hydro-geologic features able to start a potential migration of the contaminating substances through different environmental sectors;
- \( P(\theta_D) \) probability to reach a given intensity (RAI) of the release;
- \( P(\theta_E) \) probability for one of the environmental sector to be contaminated;
- \( P(\theta_F) \) probability of a plume due to the release occurred with a given intensity in a specific environmental sector;
- \( P(\theta_G) \) probability for the plume to go towards a specific direction;
- \( P(\theta_H) \) probability for the considered incident event outcome to distribute with a given intensity in a given area surrounding the contaminating source;
- \( P(\theta_I) \) probability for the target to come into contact with the dangerous substance through ingestion, inspiration or dermal contact.

Risk estimation is performed by designing the event tree and by quantifying variables and parameters involved in each previously reported groups. In particular, for a landfill, the following data are necessary to estimate the conditioned probability of each group:
P(\theta_e) Unrest. Potential Source: landfill
The needed data and information are:
Geometric Features: Area (N), Digging’s depth (N), Volume (N/V)
Operational modalities: Filling (N/V), compression (N/V), daily covering (N)
Building features: lateral sides’ bottom and final surface’ coating system (N)
Coating Systems properties: thickness (N), density (N), hydraulic conductivity (N/V)
Technological equipment features: leachate collecting system (N), biogas captation system (N), biogas combustion torches (N), biogas energy recovery engines (N)
P(\theta_h) Origin. Contamination source
Incoming waste typology: Streams (V), products typology (N/V)
Landfilled waste features: bulk density (V), hydraulic conductivity (V), humidity content (V)
Leachate’ composition (V)
Biogas’s composition (V)

P(\theta_f) Geologic formation information and description (V)
Existing water-bearing systems features and description (V)
Existing water-bearing systems identification and description (V)
Surface hydraulic bodies identification (N)
Surface hydraulic bodies quantification (V)
Identification of existing relationships between groundwater and surface waters (V)
Meteorological data: precipitations (V) winds (V)
P(\theta_g). Contaminated environmental sector

P(\theta_k) P(\theta_m). Outcome and incident outcome case

P(\theta_r). Magnitude

P(\theta_s). Exposure
Groundwater features (V)
Potential receptors identification: water-bearings (V), wells (V), watering (V)
Surface employment (V)
Potential receptors identification (V)
Figure 13. Event tree for a release of leachate from a landfill.
2.6.2. Contamination risk assessment for uncontrolled dumping of waste

Case study description
The landfill is located in a completely flat area and is about 60 km far from the built-up centre. The altimetry of the examined area is between 11 and 13 above sea level, in an area almost without whatever potential or active imbalance evidence.

The landfill geometric parameters are reported in the following Table 17.

Table 17. Landfill geometric parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta_f$</td>
<td>110.000 m²</td>
</tr>
<tr>
<td>$h$</td>
<td>17 m</td>
</tr>
<tr>
<td>$V$</td>
<td>1.870.000 m³</td>
</tr>
<tr>
<td>$S_d$</td>
<td>400 m</td>
</tr>
<tr>
<td>$W_d$</td>
<td>275 m</td>
</tr>
</tbody>
</table>

The bottom barrier parameters are (Table 18):

Table 18. Parameters of the bottom barrier of landfill.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_i$</td>
<td>100 cm</td>
</tr>
<tr>
<td>$k_i$</td>
<td>5.56E-05 cm/s</td>
</tr>
<tr>
<td>$\rho_i$</td>
<td>1.74 g/cm³</td>
</tr>
<tr>
<td>$i_z$</td>
<td>11</td>
</tr>
<tr>
<td>$\theta_z$</td>
<td>0.38</td>
</tr>
<tr>
<td>$\theta_w$</td>
<td>0.38</td>
</tr>
<tr>
<td>$h_{perc}$</td>
<td>10 cm</td>
</tr>
</tbody>
</table>

From the soils stratigraphy analysis, an average sandy clay loam soil with a 5 m power is deduced. For this kind of soil is assumed that (Table 19):
Table 19. Soil characteristics.

<table>
<thead>
<tr>
<th>Texture</th>
<th>Sandy clay loam</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_s$</td>
<td>3.64E-04 cm/s</td>
</tr>
<tr>
<td>$\theta_r$</td>
<td>0.39</td>
</tr>
<tr>
<td>$\theta_e$</td>
<td>0.290</td>
</tr>
<tr>
<td>$\theta_w$</td>
<td>0.178</td>
</tr>
<tr>
<td>$\theta_a$</td>
<td>0.112</td>
</tr>
<tr>
<td>$\theta_{wcap}$</td>
<td>0.248</td>
</tr>
<tr>
<td>$\theta_{acap}$</td>
<td>0.024</td>
</tr>
<tr>
<td>$f_{oc}$</td>
<td>0.01</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>1.7 g/cm³</td>
</tr>
</tbody>
</table>

Once the geometrical and design data of landfill are known, the geology and hydrogeology data related to the site are necessary. For the specific case of the landfill under study the first layer is located at about a 5 m depth from the land level, within an about 5 m thick stratum. The stratum top/roof is located around 10 m depth from the land level. The second layer is instead located at about 28 m depth from the land level, within an about 17 m thick stratum. In this area clay soils are found.

**Leachate production inside the landfill**

The leachate has a composition that strictly depends on the type of waste, precipitation amount and frequency. The landfilled wastes undergo many chemical/physical transformations whose final products are leachate and biogas. The leachate produced in a landfill may be qualitatively and quantitatively related to the site characteristics. In absence of such information, models simulating either leachates chemical species or production and concentration, may be used.

**Leachate flow outgoing from the landfill bottom**

The flow of leachate outgoing from the landfill may be due to the cracks in the bottom layer (generally made of polyethylene), in particular to the number of holes and their extension.

Many studies and experimental evidences verified that such discontinuities increase with time due to the material’s oxidation, caused by the leachate infiltration. For instance, 3-5 holes per surface hectare have been estimated.

The leachate is considered to infiltrate vertically by gravity, only in the landfill bottom barrier (if present), ignoring the side losses, in the hypothesis to keep low the leachate level in the landfill bottom.

The Darcy equation is therefore used

$$L_f = K_i \times i_f \times A_f$$  \hspace{1cm} (29)

where:

$L_f$ is the leachate flow going through the “mineral layer” expressed in m$^3$/s;

$K_i$ is the mineral stratum hydraulic conductivity expressed in m/s;

$A_f$ is the landfill bottom surface;

$i_f$ is the vertical hydraulic gradient, a dimensional, got through the following expression, once the mineral layer thickness ($d_i$ expressed in m) and the leachate level on the landfill bottom ($h_{perc}$), are known...
\[ i_j = \frac{h_{new} + d_i}{d_i} \]  

(30)

d_i \text{ is the thickness of the mineral layer crossed by leachate;}

\( h_{\text{perc}} \) \text{ is the leachate level on the landfill bottom.}

In the case of uncontrolled landfills without bottom waterproofing barrier, the Darcy rule is still used, but the hydraulic conductivity value is the one relating to the unsaturated soil below the waste.

**Calculation of the concentration of leachate outgoing from the landfill bottom barrier**

The model of concentration of leachate outgoing from the barrier derives from the contaminating mass balance and takes into account diffusive phenomena and chemical attenuation processes. Each of these phenomena is described by the dispersion-advection equation describing the transit/trans- 
portation of a solute in a fluid and is based on the mass balance in the interested space. The expression therefore showing the evolution of the generic species present in the leachate is given by the following equation:

\[
\frac{\partial C^L}{\partial t} = D_L \frac{\partial^2 C^L}{\partial x^2} - v \frac{\partial^2 C^L}{\partial x} - R \lambda C^L
\]  

(31)

where:

\( C^L \) \text{ is the concentration at the x distance in time t expressed in mg/l;}

\( x \) \text{ is the distance along the flow direction;}

\( t \) \text{ is the time expressed in seconds;}

\( v \) \text{ is the average speed of the liquid particles or darciana speed in m/s;}

\( R \) \text{ is the delay factor;}

\( \lambda \) \text{ is the first order decay constant, relating to the considered species and to the crossed medium, expressed in s}^{-1};

\( D_L \) \text{ is the longitudinal hydrodynamic dispersion coefficient (namely in the flow direction), expressed in m}^2{\text{/s}}.

One of the most used ways to solve it is the following equation: (Domenico and Schwartz, 1998)

\[
\frac{C^L_{\text{out}}(z)}{C^L} = \exp \left( \frac{z}{2 \alpha_x} \left[ 1 - \sqrt{1 + \frac{4 \lambda R}{v}} \right] \right) \times \text{erf} \left[ \frac{W}{4 \sqrt{\alpha_x}} \right] \times \text{erf} \left[ \frac{S_{\text{eff}}}{4 \sqrt{\alpha_x}} \right]
\]  

(32)

\( \alpha_x \) \text{ is the dispersivity coefficient expressed in cm. Such parameter is difficult to set directly, but may be determined by the following relation (Xu and Eckstein, 1995)}

\[
\alpha_{x,i} = 0.83 (\log L)^{2.414}
\]  

(33)

where \( L \) \text{ is the distance between the contaminating source and the conformity point (the conformity point may be positioned just outside the mineral stratum).}

The delay factor may be get by the following relation:

\[
R = \frac{\rho_s \theta_i}{k_d}
\]  

(34)

where

\( \rho_s \) \text{ is the soil’s density;}

\( \theta_i \) \text{ is the water volumetric amount in the generic mineral stratum;}

\( k_d \) \text{ is the substance distribution coefficient in the generic mineral stratum.}
In absence of field data the \((k_d)\) distribution coefficient may be estimated on the basis of the following equation:

\[ k_d = f_{oc} \times K_{oc} \]  

(35)

where:

- \(f_{oc}\) is the organic carbon portion in the generic mineral layer;
- \(K_{oc}\) is the water-carbon distribution coefficient;
- \(\lambda\) is the first order decay coefficient in the generic mineral layer. This parameter considers possible biodegradation processes of polluting substances.

**Pathways and possible exposure ways’ characterization**

Once the source has been characterized, all the potential pathways through which the pollutants could potentially be transported through the environmental media, must be identified.

The environmental media potentially contaminated by the leachate released by the landfill are the:

1. unsaturated area below the landfill (soil and sub-soil);
2. saturated area or water-bearing.

**Data for transportation in the water-bearing**

The water-bearings are divided in free water-bearings; i) bound water-bearings; ii) semi-bound; iii) water-bearings. The models for the transportation to the water-bearing estimation must take into account the direction of the water-bearing flow (W), the landfill extension at right angle to the landfill in the direction of the stratum flow \((S_w)\), the water-bearing thickness \((d_{sw})\), the thickness of the mixing area \((\delta_{gw})\), the hydraulic gradient of the saturated area \((i)\), the hydraulic conductivity to saturation of the saturated soil \((k_{sat})\).

The hydraulic conductivity to saturation \((k_{sat})\) shows the capacity to transmit water of a saturated soil.

The employed model gives particular attention to:

- **Darcy speed** \((v_{gw})\) simulating the motion in a saturated porous medium given by the ratio between the quantity (Q) flowing out through a portion with a right angle to the flow direction and the A section itself.

\[ v_{gw} = k_{sat} \times i \]  

(36)

- **Longitudinal, transversal and vertical dispersivity coefficients** \((\alpha_x, \alpha_y, \alpha_z)\)

In the groundwater, the contaminating substance’s crest appears under two main components:

- longitudinal, parallel to the speed vector direction and due to the speed gradients inside the single vacuum, and to the difference in the path followed by the single particles;
- transversal and vertical, both perpendicular to the speed vector direction and due to the complexity of the permeable path through the soil.

In the study of contaminating substance’ transportation and diffusion in a saturated medium, this phenomenon is considered through the dispersion coefficient \(D_x\) \((\text{cm}^2/\text{s})\). The same parameter on the basis of x, y and z axis may be modeled as follows:

\[ D_x = \alpha_x v_e \]
\[ D_y = \alpha_y v_e \]
\[ D_z = \alpha_z v_e \]

where:

\[ \alpha_x = 0.83(\log L)^{2.414} \]  

(37)

\[ \alpha_y = \frac{\alpha_x}{3} \]

\[ \alpha_z = \frac{\alpha_x}{20} \]
Transportation factors estimation

Given the concentration of the generic substance “i” contained in the leachate at the landfill bottom ($C_{S_{out}}$), the concentration at a specified distance from this release point must be calculated in order to evaluate the real exposure concentration ($C_{POE}$). In other words, the substance “i” starts its migration pathway at the landfill bottom and ends when reaches the final target. Its concentration at the target is used to evaluate if the internal exposure pathway is able to cause the target death or any health risk (e.g. cancer). The value of $C_{POE}$ is calculated through the following relation (model of leaching and attenuation):

$$C_{S_{out}} = FT \times C_{POE}$$

(38)

where:

- $FT$ is the transportation factor;
- $C_{POE}$ is the concentration at the target position.

The leaching process consists in the infiltration of the leachate through the not saturated soil area until its reaching the aquifer (saturated zone), where afterward dilution, transportation and dispersion phenomenon occur. The Leaching Factor allows the assessment of the concentration attenuation in the leachate that came out from the landfill and filtered in the lower unsaturated soil layer, until it reached the groundwater level to subsequently dilute in the surface layer. Therefore it may be said that:

$$LF = \frac{C_{layer}}{C_{S_{out}}}$$

(39)

where:

- $C_{layer}$ is the concentration in the layer;
- $C_{S_{out}}$ is the concentration going out from the landfill;

$$LF = \frac{SAM}{LDF}$$

(40)

where:

- $SAM$ is the attenuation coefficient of the unsaturated soil (soil attenuation model) taking into account the pathway followed by the polluting substance to reach the layer. By defining $d_d$ as “the depth (expressed in cm) of the leachate emission point (namely the depth, with regard to the land plane, of the landfill plane)” and $L_{GW}$ as “the groundwater depth with regard to the land plane (expressed in cm)” the $SAM$ term is obtained by:

$$SAM = \frac{d_d}{L_{GW}}$$

(41)

The $LDF$ term is the Leachate dilution factor taking into account the dilution to which the contaminating substance is subject once reached the layer, passing from the unsaturated to the saturated soil. The following expression is used to calculate the $LDF$

$$LDF = 1 + \frac{v_{gw} \times \delta_{gw}}{L_f}$$

(42)

where:

- $v_{gw}$ is the Darcy rate in the water-bearing expressed in cm/year;
- $\delta_{gw}$ is the thickness of the mixing layer in the water-bearing expressed in cm;
- $L_f$ is the leachate flow outgoing from the landfill bottom and is transported to the unsaturated area until it reaches the water-bearing, expressed in cm³/year.
With the necessary replacements we have:

\[
LF = \frac{SAM}{LDF} = \frac{1}{1 + \frac{\delta_{gw}}{L_f}} \times \frac{d_d}{L_{GW}}
\] (43)

The Dilution Attenuation Factor “DAF” expresses the ratio between the concentration at the target position \(C_{POE \text{ (groundwater)}}\) (expressed in mg/l) located at a distance from the source along the flow versus and the concentration of a contaminating substance present in the layer \(C_{Lnf}\) (expressed in mg/l):

\[
DAF = \frac{C_{POE \text{ (groundwater)}}}{C_{Lnf}}
\] (44)

Given that the entire water-bearing thickness is interested by the contamination, we have:

\[
\frac{1}{DAF} = \exp \left[ \frac{x}{2 \alpha_x} \right] \times \left[ 1 - \frac{4 \lambda_i R_i}{\alpha_y} \right] \times \left[ \text{erf} \left( \frac{S_w}{4 \sqrt{\alpha_y x}} \right) \right]
\] (45)

where:
- \(\alpha_x, \alpha_y\) are respectively the longitudinal, transversal and vertical dispersion coefficient (cm);
- \(S_w\) is the landfill extension in the direction at a right angle to the layer flow (cm);
- \(\lambda_i\) is the decay coefficient of the first order of the generic contaminating species in the leached leachate, expressed in year\(^{-1}\);
- \(R_i\) is the delay factor of the generic contaminating species in the leached leachate (\(-\)).

\[
R = 1 + \frac{k_d \rho}{\theta}
\] (46)

where:
- \(\rho\) is the soil’s density;
- \(\theta\) is the water volumetric amount in the soil;
- \(k_d\) is the substance distribution coefficient in the generic mineral stratum;
- \(V_e\) is the effective average water speed in stratum. It is obtained by dividing the Darcy speed for the effective soil’s porosity.

\[
V_e = \frac{k_{sat_i} \times \theta_i}{\theta_i}
\] (47)

**The exposure**

The E exposure factor (mg/(kg·day)) represents the daily chronic assumption of the contaminating substance. This factor is given by the ratio between the concentration, calculated in correspondence with the \(C_{POE}\) exposed target position, and the effective EM exposure quantity, which may be represented by ingested soil, inspired air or contaminated water drunk per day per body weight:

\[
E = C_{POE} \times EM
\] (48)

The evaluation of the effective EM exposure quantity is translated in the estimation of the daily amount of the considered environmental matrix, assumable by the human receptors identified in the conceptual model. The EM effective exposure quantity estimation generally is a conservative one on the basis of the Reasonable Maximum Exposure (RME). The RME is the value producing the highest exposition that reasonable is expected to be found in the site. Each RME is exposure pathway specific.
The generic equation used to calculate the effective EM exposure power (mg/kg per day) is:

\[ EM = \frac{CR \times EF \times ED}{BW \times AT} \]  

(49)

where:
- CR is the contact factor, namely the amount of each environmental medium ingested, inspired or with which a contact occurred per time unit or event. It’s expressed in m³/day for water and air and in mg/day in the case of soil;
- EF is the exposure frequency days/years;
- ED is the exposure length;
- BW is the body weight in kg;
- AT is an individual average exposure time to a substance expressed in days.

To calculate the EM effective power we have:

\[ EM = \left( \frac{1}{kg \times day} \right) \times \frac{(IR \times EF \times ED)}{(BW \times AT)} \]  

valid for water ingestion  

(50)

**Calculations results**

The pathway of the leachate throughout the environmental media starting from the landfill bottom to the target position is schematically reported in the Figure 14.

![Figure 14. Scheme of the contaminants pathway.](image)

The use of the above briefly described transportation models allows to estimate the pollutants’ concentration at the target (Table 21) that is a water supply well located 100 m away from the landfill. By considering that the internal exposure pathway is the water ingestion of a human the “exposure” factor E can be calculated for human target (Table 22).
Table 20. Parameters for E evaluation.

| Outgoing flow from the bottom of the landfill | $L_f$ | 6.78E05 cm$^3$/s |

Table 21. Variables for E evaluation.

| Arsenic | 4.85·10$^{-3}$ | 9.39·10$^{-4}$ | 1.60·10$^{-3}$ | 7.89·10$^{-4}$ |
| 1,1,2,2-tetrachloroethane | 4.5 | 2.31·10$^{-10}$ | 3.95·10$^{-10}$ | 1.04·10$^{-10}$ |
| Benzo(α)pyrene | 5.5 | 1.59·10$^{-196}$ | 2.70·10$^{-196}$ | 1.53·10$^{-133}$ |
| Benzene | 5 | 6.52·10$^{-3}$ | 1.11·10$^{-2}$ | 5.29·10$^{-3}$ |

It was chosen as a possible exposure scenario the water ingestion of groundwater, the results are (Table 22):

Table 22. Exposure for humans calculated for the water contamination by landfill leachate migration.

<table>
<thead>
<tr>
<th>Exposure adults (mg/l)</th>
<th>Exposure children (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>2.27·10$^{-2}$</td>
</tr>
<tr>
<td>1,1,2,2-tetrachloroethane</td>
<td>4.48·10$^{-10}$</td>
</tr>
<tr>
<td>Benzo(α)pyrene</td>
<td>6.56·10$^{-233}$</td>
</tr>
<tr>
<td>Arsenic</td>
<td>3.38·10$^{3}$</td>
</tr>
</tbody>
</table>

Two different indexes can be used to estimate the cancer risk: the SF index also known as the slope factor (i.e. the slope of the dose-response function expressed in mg/kg-day) and the URF, the unit risk factor (i.e. a concentration expressed in μg/m$^3$). The product of the SF and the exposure gives the risk index (Table 23):

Table 23. Risk indexes calculated for the water contamination by landfill leachate migration.

<table>
<thead>
<tr>
<th>SF</th>
<th>Risk adults</th>
<th>Risk children</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>5.50·10$^{-2}$</td>
<td>1.25·10$^{-3}$</td>
</tr>
<tr>
<td>1,1,2,2-tetrachloroethane</td>
<td>2.00·10$^{1}$</td>
<td>8.95·10$^{-11}$</td>
</tr>
<tr>
<td>Benzo(α)pyrene</td>
<td>7.30·10$^{1}$</td>
<td>4.79·10$^{-233}$</td>
</tr>
<tr>
<td>Arsenic</td>
<td>1.50</td>
<td>5.70·10$^{-3}$</td>
</tr>
</tbody>
</table>

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3. **Multi-risk assessment of a case-study**

The case-study of the Casalnuovo municipality, developed during the NaRaS project, is used to describe a possible procedure for multi-risk assessment.

Casalnuovo is a municipality of the Campania region located 12-13 km NE of the crater of Mt. Vesuvius volcano. The resident population is 47940 and the town consists of 3615 buildings, most of them being apartment houses. Several public (f.i. schools) and commercial buildings are located mainly at the outskirts of the town. Because of its location Casalnuovo is exposed to adverse events from different sources: Mt. Vesuvius volcano, the Irpinia tectonic earthquake source, a small river passing through the municipality. The presence of industries and illegal landfills widens the number of possible threats (Figure 15).

![Figure 15. The Casalnuovo municipality, the main anthropogenic risk sources and distribution of different buildings and infrastructures.](image)

A sound multi-risk assessment is fundamental to give answers to typical questions posed by local authorities. What is the most dangerous hazard that threatens the municipality? If we have some resources for mitigating risks, where we have to invest our money?

A direct comparison of single risks threatening Casalnuovo is hard to do with the available data since they are referred to quite different time windows and typologies of damages. Moreover, possible triggering effects were not considered at all. Risk ranking and risk assessment including possible triggered (cascade) events are basic issues to be approached by a multi-risk analysis and they will be the final goal of this chapter.
3.1. Ranking the risks

The ranking of risks requires that each typology is calculated using the same boundary conditions. First of all it is necessary to define a common timeframe, and the specific kind of damage we are interested in. Here, for the sake of example, we set the timeframe to one year, and we focus our risk analysis on a damage consisting of human life loss.

3.1.1. Seismic risk in Casalnuovo

The most recent evaluation of the seismic hazard in the Casalnuovo area, as provided by the National Seismic Hazard Map (www.INGV-zonesismiche.mi.ingv.it), is represented in Figure 16. The 90th percentile of the peak ground acceleration in the next 50 years is in the range 0.15-0.175 g. An estimate of annual individual seismic risk requires further elaboration of the information given by the hazard map. By using the classical relationship between peak ground acceleration (amax) and macroseismic intensity (I), we know that the 0.15-0.175 g range of acceleration corresponds to I = VII. An event with this intensity has a 10% probability of occurrence in 50 years. Hence, the annual probability of occurrence for such event is about pVII = 0.002. The probability of occurrence of an Intensity VIII can be evaluated taking into account that one degree in Intensity corresponds roughly to half degree in Magnitude. This means that pVII/pVIII is about 3, therefore, pVIII = 0.0007.

Figure 16. Seismic hazard in the Casalnuovo area (amax are in units of g).

In order to estimate the expected damage for such a kind of event, we have to assume the vulnerability of the buildings, the level of damages, and how these parameters reflect on the probability of having casualties. The relationship between intensity (I) and degree of damage has been defined for some municipalities close to Casalnuovo by Zuecaro et al. (2008) for the 2007 version of the Italian Civil Protection Emergency Plan of Mount Vesuvius. Buildings have been gathered in four categories (from A to D) according to their structural characteristics. Five levels of increasing damage have been defined.
The probability of damage (y-axis) of an earthquake of intensity VIII as a function of possible damage level (x-axis) for four different building typologies is reported in Figure 17. Casalnuovo has prevalent D type buildings, as the surrounding areas (see for example, Figure 15 in Zuccaro et al. 2008).

Using the plot in Figure 17 the expected damage corresponding to I=VIII will be
- Damage 4 = 0.1%
- Damage 3 or less = 99.9%
- Earthquakes of I = VII will produce Damage level less than 4 in the Casalnuovo area.

It can be assumed that only Damage level 4 (partial collapses) or more can lead to casualties of people living inside the buildings. Therefore no risk for people can be assumed for I=VII. Specifically, a person living in a building suffering Damage 4 has 5% of probability to be killed (Zuccaro et al., 2008).

The risk for human life can be estimated assuming that the number of people staying on average inside one building is given by the total number of citizens (47940) divided by the number of edifices (3615), i.e., 13.26. This is a very rough assumption, since we assume that all citizens will be inside a building at the time of the earthquake. Actually, this number will be lower, but in this way we accommodate partially the possible death of people on the street caused by a building collapse.

The risk for human life $R^*_{\text{seis}}$ is composed by three factors: the probability of occurrence of a I=VIII earthquake, the average number of edifices with expected damage level 4, and the average number of people killed inside a building with expected damage level 4. Such a probability is:

$$R^*_{\text{seis}} = 0.0007 \times (0.001 \times 3615) \times (0.05 \times 13.26) = 0.0017$$

3.2. Volcanic risk assessment: the ash fall hazard

Historical data indicate that ash fall is the main adverse event due to eruptions of Mt. Vesuvius in the Casalnuovo area. Due to volcano morphology and the distance from the volcano, other possible adverse events, such as pyroclastic flows, lava flow, and lahars, have been very rare in this area. Actually, Casalnuovo is out of the red zone of danger defined by the Mt. Vesuvius Civil Protection Emergency Plan, but it is well within the zone under threat of ash fall. However, we remark that the inclusion of such events do not pose further conceptual problems.

We use the strategy described in 2.2 of this book. The set up of the conditional probabilities at each node is taken by Marzocchi et al. (2004). In the following, we report only the results of the full Probabilistic Volcanic Hazard Assessment for different ash thickness.
3.2.1. Probability of ash fall in Casalnuovo

The annual probability of Ash Fall in Casalnuovo can be estimated using the probabilities at the nodes at the Bayesian event tree, as indicated in par. 2.2. and in Marzocchi (2004, 2006):

$$[\pi] = 12 \sum_{\text{VEI}} [\theta_1] [\theta_2] [\theta_3] [\theta_4^{(\text{VEI})}] [\theta_6^{(\text{TF})}] [\theta_7^{(\text{Casalnuovo})}] [\theta_8^{(\text{threshold})}]$$

where the summation is for eruptions with Volcanic Explosion Index (VEI) (3, 4, and 5+), and the factor 12 transforms the month probability (see node 1 and 3) into annual probability. We stress that this approximation holds when the probabilities are small as in the present case. The multiplication is performed through 1000 values randomly selected for each node. At the end, we have four distributions, each one relative to a specific thickness. These distributions are reported in Figures 18-21.

Figure 18. Tephra fall hazard map for Mount Vesuvius. The dialog box reports the 10th, 50th, and 90th percentiles of the annual probability of exceedence of a thickness of 10 cm.

Figure 19. The same as Figure 18, but related to a thickness of 20 cm.
Figure 20. The same as Figure 18, but related to a thickness of 40 cm.

Figure 21. The same as Figure 18, but related to a thickness of 60 cm.

The Figures 18-21 represent the exceedence probabilities calculated in a time frame of 1 month. The annual probability for any specific thickness can be approximated as:

\[
P_{10} = P(10 < \text{thickness} < 20) = 12 \times (0.0003 - 0.0002) = 0.0012
\]
\[
P_{20} = P(20 < \text{thickness} < 40) = 12 \times (0.0002 - 0.0001) = 0.0012
\]
\[
P_{40} = P(40 < \text{thickness} < 60) = 12 \times (0.0001 - 0.00007) = 0.00036
\]
\[
P_{60} = P(60 < \text{thickness}) = 12 \times (0.00007) = 0.00084
\]
In order to retrieve the individual risk we need to incorporate the vulnerability. Using a density of 900 kg/m³ for dry ash deposits and the probability of collapse as a function of the load reported by Zuccaro et al. (2008), the probability of collapse $P_c$ for different thickness of the ash deposits on the roofs of a building of C1r category (Fig. 4 Zuccaro et al., 2008) is:

$P_c(10\,\text{cm}) = 0.00$
$P_c(20\,\text{cm}) = 0.01$
$P_c(40\,\text{cm}) = 0.15$
$P_c(60\,\text{cm}) = 0.60$

The collapse from ash fall can be compared to a Damage 4 for seismic risk. If we assume, that the probability for human beings living inside the building to be killed by a collapse is 0.05 (the same as in the case of earthquakes), the annual volcanic risk for human life is

$$R^*_{volc} = 0.0012 \times (0.01 \times 3615) (0.05 \times 13.26) + 0.00036 \times (0.15 \times 3615) (0.05 \times 13.26) + 0.00084 \times (0.60 \times 3615) (0.05 \times 13.26) = 1.37$$

3.3. Hydrogeological risk assessment

The geological nature, the topography, the climatic conditions and particularly the carefree use of land have made Campania one of the Italian regions with the highest hydrogeological risk. Exposure to hydrogeological risk is therefore a problem of great social relevance, both for the number of potential casualties and for the high exposed value, consisting of homes, industries, infrastructures, life-lines and cultural heritage. Possible change of scenarios in relation to climate change are of further concern for the near future.

In Italy, the identification, delimitation and outlining of the boundaries of the areas that present flood and landslide hazards and risks are under the competence of the River Basin Authorities, established by the Law 183/89 and identified as the responsible authority for the basin planning. Each River Basin Authority used different criteria for the definition of the areas at landslide or flooding risk. The following flood hazard map is the result of the harmonization for the Campania territory of the information given by each local River Basin Authority:

*Figure 22. Map of the flood hazard in Campania.*
The Casalnuovo territory does not have significant landslide hazard. Flooding risk is moderate (R1 or R2) in some localized areas of the municipality due to a hazard of level P1 (see Figure 23):

![Figure 23. Map of flooding hazard in Casalnuovo.](image)

The annual probability of being killed by a hydrogeological event for the inhabitants in the Casalnuovo municipality has been evaluated using the AVI catalogue and average number of inhabitants. The AVI catalogue reports the number of casualties in Campania Region for each event and the historical sequence of event. The result has been downscaled to the Casalnuovo number of residents. The results are:

![Figure 24. Map of flooding risk in Casalnuovo.](image)
\[ P_{\text{flooding}} = 1.4 \cdot 10^{-7} \]
\[ P_{\text{Landslide}} = 2 \cdot 10^{-8}. \]

From these numbers the annual risk for flooding (\( R^{*}_{\text{flood}} \)) and for landslide (\( R^{*}_{\text{land}} \)) can be calculated. Looking at similar past events in Campania Region, we can assume that a landslide impacts few tens of inhabitants, while a flood can impact one order of magnitude larger. Therefore, we can estimate

\[ R^{*}_{\text{flood}} = 1.4 \cdot 10^{-7} \times 300 = 4.2 \cdot 10^{-5} \]
\[ R^{*}_{\text{land}} = 2 \cdot 10^{-8} \times 30 = 6 \cdot 10^{-7} \]

### 3.4. Industrial and environmental risks

The multi-risk approach has been applied to a case-study developed in the area of Casalnuovo (Naples). The map of the Casalnuovo municipality, reported in Figure 15, shows the localization of the industrial and environmental risk sources (A: industrial site for LPG storage; B: illegal landfill) that can generate adverse events in the area.

Here, we consider only the highest risk that is due to a collapse of a pipebridge; this adverse event has been described in paragraph 2.4 (industrial risk).

In this section we evaluate the conditional probability to have casualties death due to the exposure to the heat flux generated by the fire of the LPG released by the pipelines after its collapse. The products of the LPG fire form a cloud that includes compounds having a density higher than air so they fall on the surface and contaminate it. The soil and the superficial water constitute the starting point of a contamination pattern throughout soil, subsoils, ground water. In our scenario the risk due to the exposure at a specific compound (benzene) is considered. By taken into account the exposure pathways, the spatial distribution throughout the environment media, the critical value of the benzene concentration that causes humans death, the annual risk index for this scenario has been evaluated.

#### 3.4.1. Risk estimation

The industrial risk source chosen for the multi-risk evaluation is the pipebridge located in an industrial site of Casalnuovo.

In the following the probability of each section of the event tree are reported (see also section 2.4):

\[
P(\theta_b) = 2.09 \cdot 10^{-4} \\
P(\theta_c) = 6.5 \cdot 10^{-2} \\
P(\theta_f) = 1.25 \cdot 10^{-1} \\
P(\theta_d) = 5 \cdot 10^{-1} \\
P(\theta_j) = 2.16 \cdot 10^{-1} \\
P(\theta_i) = [1: 0.01] 
\]

The individual risk is then:

\[ \text{ir}_i = \prod_{j=4}^{7} \theta_{ij} \]

By applying the product of the probability values for each event, the following individual risk index range is obtained for the death of population in the risk area (117 m from the risk source localization):

\[ 1.83 \cdot 10^{-7} < I R < 1.83 \cdot 10^{-9} \]
Assuming that 10 people will be in that area of influence (117 m from the explosion), we can estimate the direct annual industrial risk as

\[ 1.83 \times 10^{-6} < IR < 1.83 \times 10^{-8} \]

The products of the LPG fire will be transported by the wind until a distance that depends by meteorological characteristics and physico-chemical properties of the cloud formed after fire/explosion of released LPG. These products are transported throughout the air and deposited on the soil or on the superficial water surface; these environment media are the starting media of a contamination pathways that can arrive to different targets: for example to the humans. In the case of a specific exposure pathway (indicated in the following scheme) the probability of death due to ingestion of toxic compounds can be determined. For instance the probability to have a death due to ingestion of water contaminated by benzene is:

\[ IR = 1.25 \times 10^{-3} \]

Also in this case, we need to assume the number of people that will be affected by the threatening event. In this case, taking into account the area involved by the contamination, it is reasonable to assume 100 people. Therefore, the annual risk for environment is

\[ R_{env}^* = 1.25 \times 10^{-3} \times 100 = 0.0125 \]

### Ranking the risks

In the following we summarize the annual risks for human life.

- \[ R_{seis}^* = 0.0017 \]
- \[ R_{vulc}^* = 1.37 \]
- \[ R_{flood}^* = 4.2 \times 10^{-5} \]
- \[ R_{land}^* = 6 \times 10^{-7} \]
- \[ R_{ind}^* = 1.83 \times 10^{-6} < IR < 1.83 \times 10^{-8} \]
- \[ R_{env}^* = 0.0125 \]

#### 3.5. Multi-risk due to triggering effects

The consideration of triggering effects and/or cascade adverse events may be of extreme importance to obtain a reliable multi-risk index. Here, we explore one possible triggering effect scenario described by the following sequence of events:

Volcano (risk source) → Eruption (event) → Ash fall (phenomenon) → building collapse (damage) → Structural failure of civil infrastructures in the industrial plant (damage that allows the “activation” of the risk source “LPG plant”) → Toxic release / fire / explosion (event) → Substance leakage / Thermal Flow / Pressure Wave (phenomenon) → Environmental air, soil, water contamination (damage that becomes risk source if exposure pathways are active) → contaminant migration (event) → absorption by plants roots and/or inlet into superior organism by direct exposition routes (ingestion, inhalation, dermal contact) (phenomenon) → casualties, acute health damage, chronic health damage (damage).

This series-parallel cascade scenario is one of the possible scenarios that can be identified. Each hypothesized scenario must be quantified by means of probability of its occurrence. If N scenarios are identified and quantified the multi-risk index will be, more correctly, an array of risk indexes. This array is formed by risk index calculated on the basis of multi-hazard scenarios and risk index calculated by considering the single risk source (e.g. in this latter case it has not been possible to individuate any interaction between different risk sources) (Figure 25).
Figure 25a. Scheme of interactions among different adverse events in a cascade triggered by ash falls due to an eruption of Mt. Vesuvius.
Figure 25b. Scheme of interactions among different adverse events in a cascade triggered by ash falls due to an eruption of Mt. Vesuvius.
Figure 25c. Scheme of interactions among different adverse events in a cascade triggered by ash falls due to an eruption of Mt. Vesuvius.
This scenario can be summarized as follows: while a 10 cm thickness of ash does not have virtually any direct effect on human beings because it does not lead to building collapses, it originates collapse of pipebridge inside the industry, causing an explosion and the subsequent air and water contamination. In fact even 10 cm of ashes can produce a load of about 100 kg/m² (even more if they are wet), sufficient to damage structures not designed to withstand vertical loads. The annual probability of a single industrial risk for a pipebridge damage is $2.09 \times 10^{-4}$, while the annual probability to have a 10 cm thickness or more on the industry is $3.6 \times 10^{-3}$, i.e., more than one order of magnitude larger. This means that, keeping the probability to all other nodes equal, the industrial risk in Casalnuovo is underestimated one order of magnitude if considered alone.

From the volcanic risk point of view, although a small accumulation of ash does not lead to any building collapse, it could produce casualties through an industrial/environmental accident, therefore increasing also the volcanic risk. The scheme links the event trees, connecting the probability to have 10 cm or more of ash fall to the node of the industrial risk where the pipebridge collapse is taken into account. In practice, this leads to an increase of the volcanic and industrial/environmental risk as well.

3.5.1. Using risk and multi-risk for selecting mitigation actions

In the previous paragraphs, we have shown that a multi-risk approach provides a global perspective of the possible threats for a municipality. In our case, we have made a rank of possible risks, using classical risk approaches. The comparison is made possible only using the same time window and the same kind of damage (here, the human life loss). For Casalnuovo we saw that the volcanic risks overwhelm significantly all the others. We have also shown that both volcanic and industrial/environmental risks can be underestimated if we do not consider the interaction among them.

The final consideration is on the meaning of multi-risk for planning mitigation actions. We argue that mitigation actions have to be focused not necessarily on reducing the highest rank risk. A rational mitigation policy has to focus on the risks that could be mostly reduced. In other words, it is not rational to spend all the money to reduce of 0.1% the highest risk, when with the same amount of money we can reduce significant percentages of all others. We argue that mitigation actions have to be decided considering the multi-risk assessment together with a sound cost/benefit analysis.
References

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<table>
<thead>
<tr>
<th>Nº</th>
<th>Climate Change and Natural Hazards Publications</th>
<th>EUR</th>
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| 1   | EUROPEAN RESEARCH ON CLIMATE CHANGE  
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Multi-risk evaluation is a relatively new field, until now developed only partially by experts with different backgrounds. The EC FP6 NARAS project initiated some consideration and reflection on this topic. As mentioned by Durham, a joint analysis and quantification of all the anthropogenic and natural risks which can affect a territory (multi-risk approach) is a basic factor for development of a sustainable environment and land use planning as well as for competent emergency management before and during catastrophic events. This is the aim of this publication that will present ideas and concepts: - report the principles and rationales that stand behind a procedure for multi-risk assessment; - provide a description of the most advanced procedures generally adopted to estimate individually natural and anthropogenic risks representing major threats for Southern Europe; - tackle directly the problem of multi-risk assessment applying innovative procedures and protocols to the case study of a town close to Naples (Casalnuovo).