Sustainable development and risk: Flood hazard and vulnerability assessment. Methodological proposal and application.

D. Berzi\textsuperscript{1}, A. Colucci\textsuperscript{2}, S. Mambretti\textsuperscript{1}

\textsuperscript{1}D.I.I.A.R.

\textsuperscript{2}D.I.A.P.

Politecnico di Milano, Milano, Italy

Abstract

The basic definitions of hazard, vulnerability and risk introduce the paper. Then, a comparison between different models for flood hazard assessment is performed, with application on a case study area (San Benedetto PO). Afterwards, vulnerability maps and risk evaluation are carried out for the area and thus risk evaluation. Finally some considerations about the reliability of different models proposed are drawn.

1 Introduction

The importance of studies integration between territorial risk assessment and planning instruments has increased in the last decades. This approach allows improving the prevention measures and the implementation of non-structural measures. Moreover, integrated studies presented could represent the base for the decision-making process (political and technical).

First of all, it is necessary to define the risk key-words, as in literature contrasting definitions could be found. Then we will focus on the hazard and vulnerability assessment in an Italian case study (S. Benedetto Po, on the river Po). For the hazard evaluation, different hydraulic models have been applied. These have a degree of complexity constantly increasing, in order to determine the more appropriate approximation level to the studied problem. They are both
of the one-dimensional type (in order to model the hydraulic wave inside the river) and of the two-dimensional one (in order to model the flooded area). As obvious, not always a complete and very complex mathematical model is desirable, because it requires a lot of effort for its implementation and an availability of many and good data about the territory. In the paper results obtained from the application of these models are discussed.

Risk assessment is performed through the convolution of two parameters: hazard and vulnerability. The research aims were: produce risk-maps (to visualize the different risk-levels on the territory), compare the different planning instruments, and verify the coherence between planning guidelines and measures for risk prevention and mitigation (Conti and Lurago, [1]).

As far as the Italian laws framework and the planning instruments are concerned, see the parallel study (Colucci et al., [2]).

2 Preliminary definitions

Hazard \((H)\). In literature this concept has different definitions. In relation to natural phenomena, the most accepted definition is stated in the UNESCO report (Varnes et al., referenced in [3]): “probability of occurrence of a potentially dangerous event in a fixed time range and in a fixed area”. In this definition the concepts of time and space are explicitly stated, but the event magnitude concept is not mentioned. See also Canuti and Casagli [4].

The Einstein approach [5] is quite different. The hazard concept definition is based on the geometrical and mechanical characteristics of the natural phenomenon. In this way the concepts of magnitude and area of potentially dangerous events are explicit. (It follows that) The hazard definition could be the “probability of occurrence of a danger in a fixed time range”.

In practice, hazard is described in different ways in relation with the study topic/issue (earthquake, volcano eruptions, landslides, avalanches, etc.). The return period \(T_R\) is often used in order to characterise the events with fixed magnitude in a specific area.

The Italian law (DPCM 10/6/1998) states that the flooding events with \(T_R = 50, 100, 200\) and 500 years have to be studied.

A relevant aspect is the spatial propagation of the phenomenon. It is neglected in Varnes’s definition and in later ones. If the propagation is neglected, the risk analysis results uncompleted, because it is limited to beginning of the process. It is equally important, instead, the probability that the wave reaches at a certain time, a certain place. In this case it seems more appropriate to define it as induced hazard.

Exposition \((E)\). It can be defined as “probability that a certain element be exposed to the risk when an event of fixed magnitude, in a fixed time range and in a fixed area, occurs” [6]. Different authors define \(E\) as “probability that an element be subject to a fixed hazard”.

In literature \(E\) is also defined as a quantitative index to sum up the number of persons and goods potentially subject to the event (Menoni, [7]).
Vulnerability \((V)\) could be defined as inverse of the resilience. Resilience describes the capacity of ecosystems to react against the stress. The vulnerability represents the territorial system tendency to suffer damages during a catastrophic event (Grandori Gaugenti and Brambilla [8], Colucci et al. [1]).

Risk \((R)\) is the total damage obtained for a specific event: \(R = H \cdot V \cdot E\) (Autorità di Bacino del Po, [9])

3 General procedure

The risk assessment and mitigation general procedure could be summarized on different levels:

- **Description of the state of the nature.** In this phase, basic information on the state of the nature, on the factors responsible for dangerous events, and on the effects of these phenomena on the territory, are collected.
- **Evaluation of the magnitude.** It means characterising phenomena as a function of their intensity (for instance: depth of the hydraulic wave, flood area extension, velocity of lava flow, earthquake magnitude, etc.).
- **Evaluation of hazard.** It is evaluated the probability of occurrence of an event in a fixed time range, area and with a fixed magnitude. This evaluation is the key step of the procedure and can be performed in different ways
- **The vulnerability assessment**
- **Risk evaluation.** This phase is articulated in two steps:
  1. individuation, description and assignment of a value to each element at risk;
  2. actual risk evaluation, as convolution (or combination) of hazard and vulnerability.
- **Risk management.** In this phase the acceptable risk level has to be evaluated. Moreover, risk mitigation actions have to be performed (in relation to the hazard or vulnerability aspects). These actions could comprehend monitoring projects, planning measures, or, even, structural measures.

4 Flooding hazard evaluation

In the paper two type of models have been used: the former is one-dimensional in order to evaluate the discharge variation inside the river bed; the latter is two dimensional in order to evaluate the actual flooded area and the wave propagation velocity outside the river bed.

In order to build an instrument that is useful for the Administration, it has been considered very important to verify the approximation that can be obtained using simpler models, also keeping in account the lack of specifically trained staff.

The event used in all simulation has return period equal to 200 years, as this is the value to be adopted when designing embankments in Italy.

As for one dimensional models, three have been used. The first based on uniform flow hypothesis (and so not accepted by Italian law to design or verify hydraulic structures), the second based on steady flow hypothesis and the third based on
the unsteady flow equations. The Manning roughness coefficient $n$ has been assumed equal to 0.04 $m^{1/3}/s$, with no differences between main channel and floodplains. This value is typical for a river with sparse vegetation in the floodplains and with irregular embankments (Chow [9], French [10]).

River profile is extremely irregular in the case-study, with positive and negative slopes, so that it has been decided to use the mean value of slope, which is equal to 0.001.

The results are quite different from those obtained by the “Autorità del Bacino del Po” [3], characterised with velocity values equal to about 4 $m/s$ and discharges equal to about 12000 $m^3/s$ with a water level around 25 m o.s.l. Obtained results show instead a clear under-estimation of the discharge and velocity values. Supposing that the differences depend on the evaluation of the slope $i$, some trials have been carried out.

In figure 1 different discharge – water level curves are shown, as a function of the slope. Differences and uncertainties are obvious. It is observed that uniform flow law is very sensitive to the slope parameter, so that it seems reasonable not to employ it.

Much better results are carried out when using the steady flow model. In this case, indeed, depth matches the prevision of [3] for the reference discharge value of 12500 $m^3/s$.

![Fig. 1: Comparison of Q-h curves when varying the slope estimation.](image-url)

In the study of unsteady flow, we used as upstream boundary condition a wave with return period $T_R = 200$ years (Adami and Gardelli [11]). It is possible to see that results of unsteady and steady flow study are very similar. Consequently it is to be preferred the employment of the steady flow approximation for most cases; the unsteady flow simulation should be used only for the most complex or peculiar situations.
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As regarding the flood propagation out of the river bed, a simplified breakage scenario of the main embankment has been built. The breach has been positioned according to the vulnerability of the land, discussed in the following paragraph, and on the analysis of former events on the section identified as 46 in the Bartnosi numeration [3], with distance from the source equal to 486 km. The breach is assumed to be 4.5 m height and 100 m long in an embankment 23.5 m height on sea level. Dimensions have been estimated from data collected after a breach happened in 2000 in the same place.

The first potentially flooded area delimitation criterion considered is the one used for the determination of C zone arranged by "Autorità di Bacino del Po" [3]. It is a pure geometric method that, once evaluated the maximum water depth in the river bed for an assigned return period, considers as floodable areas the ones with lower elevation. Even if this method may bring reasonable results when the river has a lower elevation than the surrounding land, it is clearly not feasible when, as in this case, the free surface of the river is well above the surrounding land, because the obtained results are an over estimate of reality and bring too high hazard value. This result is clearly wrong because it does not keep in account the distance from the breakage. The volume of wave, in fact, even if it is very large, it is still finite. This method, moreover, does not allow to estimate the forces the wave performs on the houses, bridges etc. that it faces when moving.

A probably more rational criterion keeps in account both the elevation and the distance from the breakage with a weighted matrix for the hazard evaluation. Tuning of this method might consist to evaluate the weights to be assigned to those parameters, but the calibration results are quite difficult to generalise; moreover, the calibration procedure could excessively complicate a simple method, which has as a goal to easily produce results with a good degree of confidence, but that cannot substitute more complex and physically based models. Evaluation of hazard areas with this method are shown in figure 2.

Hydraulic simulations have been also performed with the program FLO - 2D, which uses a two dimensional scheme for integrating the Saint Venant equations, in order to evaluate the degree of confidence of the method. The first phase of modelling is related to the development of a regular grid, which is over imposed on a map (in adequate scale) of the floodable area. In this case elevations of the CTR (technical regional maps) in the San Benedetto Po area have been used. It has been chosen to build a square grid with 100 m long side, as compromise between accuracy in computations and computer run time. For each square the barycentre elevation and the roughness value (in this case chosen constant and equal to 0.033 m^2/s) have been assigned. The breakage happens when the wave has a level equal to 21.0 m on sea level. The wave is the above mentioned one with return period equal to 200 years (see fig. 3). The flow through the breakage has been simulated as overflow, with \( Q_{out}(t) = \mu \cdot h(t) \cdot L \cdot \sqrt{2g \cdot h(t)} \) and where the coefficient \( \mu \) is assumed equal to 0.385. The overflow depth has been computed as \( h(t) = H(t) - h_{threshold} \) where \( H(t) \) is the wave level in the section 46 at time \( t \) and \( h_{threshold} \approx 23.5 - 4.5 = 19.0 \) m on sea level.
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Figures 4 and 5 show the flooded areas after respectively 3 and 24 hours. The agreement with the ones obtained through the simplified method (see figure 2) seems quite satisfactory.

![Map of flooded areas with key](image)

**Fig. 2:** Hazard evaluation through a simplified topographic method.

![Graph of wave](image)

**Fig. 3:** Wave employed for the simulation of the unsteady flow in the river bed.
Fig. 4: Flooded area after 3 hours from the breakage.

Fig. 5: Flooded area after 24 hours from the breakage.
5 Vulnerability assessment

The vulnerability assessment is based on the overlay mapping model (Mc Harg [12]). The evaluation factors are referred to the territorial system components.

Settlement system. The evaluation factors are: the population vulnerability, the land uses vulnerability (residential, industrial, commercial and service areas), the critical facilities vulnerability. The priority assessment criteria are the safeguard of the population’s health and secondly the economical issue.

Agricultural system. The assessment factors are: the agricultural land uses (considering as parameters the landscape importance and the economical productivity) and the breeding farms presence (the breeding-farms are evaluated through two parameters: economic importance and the potential pollution hazard).

Lifelines system. This system concerns the road network, the railway system, the electric network and the irrigation system (during the flood event the lifelines strategic importance is plain).

Physical-natural system. The analysed factors are: altimetry, morphology, lithology and geology characteristics, the water-table vulnerability and the land capability.

The homogeneous vulnerability areas are defined through the overlay of single components assessment. The last assessment step needs also to define the vulnerability resulting from the relations between the territorial components.

An example of final step assessment criteria is summarised in table No.1, and the figure 6 shows the settlement system vulnerability maps.

<table>
<thead>
<tr>
<th>Homogeneous Vulnerability areas</th>
<th>Assessment criteria (Settlement and lifelines system assessment factors)</th>
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Table 1: An assessment criteria example
6 Conclusions

In the paper the different definitions of the risk key-words have been presented. A case study has been selected in S. Benedetto Po, on the side of the Po River. Hazard and vulnerability have been evaluated using different methods that have an increasing level of complexity. Especially for the hazard evaluation different methods, ranging from the simply topographic to the full hydraulic ones, have been applied. Their feasibility has been commented, finding a good compromise between accuracy and simplicity. In fact, it has been shown that it is not always necessary to use full models, as very often a lower level of accuracy produces practically the same results. Vulnerability maps have been shown, giving indication for a simple method to produce them. As convolution between hazard and vulnerability is risk, a comprehensive method for risk evaluation has been drawn in the paper. In the parallel research (Colucci et al., [2]) the Italian laws for planning and action have been commented on the basis of the present paper.
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References


This document refers to the report UNESCO, 1984, that refers to the UNDRO proposals (Office of United Nations Disaster Relief Coordinator).


