Chapter 7
Hydrologic Disasters: Assessing Hazard and Risks

Gianfranco Becciu, Mariana Marchioni, Anita Raimondi, and Umberto Sanfilippo

Abstract Hydrologic disasters can be more frequent and especially severe in highly urbanized areas, causing considerable human and property losses. Climate alterations may lead to more extreme rainfall events on small portions of the watershed, while urbanization increases impervious surfaces, reducing subsoil infiltrations and leading to an increment in runoff peak flow and volume. An essential tool to reduce damage and improve hydrological disaster management and mitigation is a proper assessment of hazards and risks. Hazard estimation requires detailed knowledge of watershed characteristics and hydrological processes. Semi-probabilistic approaches can be used for hazard estimation, allowing to derive the probability distribution functions of runoff variables from those of input variables. Risk assessment includes also the evaluation of exposure, that is human lives and other values which may be involved, and vulnerability, which represents the lack of resistance to damaging or destructive forces. Risk maps and matrixes can be used as tools to identify and prioritize risk mitigation actions. This chapter covers hazard and risk assessment for hydrologic disasters and presents two applications in case studies located in highly urban watersheds in Milano (Italy) and San Paolo (Brazil).

Keywords Hydrologic disasters · Risk assessment · Hazard assessment · Floods · Milano · San Paolo

1 Introduction

Hydrologic processes rule the transformations, the movement, and the storage of water in time and space, inside the Water Cycle. These natural processes, happening all over our planet with different features, are well-known in their general forms and can be analyzed and modeled at different time and space scales.

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Risks may arise from hydrologic processes when quantitative features, in time and/or in space, of one or more components of the Water Cycle (precipitation, surface runoff, evapotranspiration, etc.) become significantly different from mean values. This shift from the "normality" of a hydrological event is usually measured in terms of probability of occurrence or, more empirically, of rank in the historical range of records. Often, adjectives like "extreme", "rare", or "exceptional" are used for this kind of event, to express the concept that a limit threshold was passed. More formally, this threshold is defined as the 5–10% quantile in the right or left tail of the probability distribution of a hydrologic parameter or as the 5–0% upper or lower ends in the range of its records.

Extreme events are considered disasters when they lead to human, material, economic, or environmental losses and impacts (UNDRR, 2007). Disasters resulting from the hydrologic process include storms (hurricanes, typhoons, and cyclones), floods, droughts, tsunamis, landslides, dam breaching, mud and debris flow, and sea-level rise (Singh, 2012). Disasters are more frequent and significant in highly urbanized areas, where extreme events may cause more losses and impacts, due to the greater density of population, infrastructures, and social and economic activities. In these areas, the risk of flooding is often the main concern.

Floods are normally a consequence of extreme rainfall events, but they can also happen because of infrastructure failures, such as dam breaches or river embankment collapse. They are often affected by anthropic land alterations, such as changes in soil use, floodplain reduction and occupation, and riverbed covering (Jah et al., 2012; Pahl-Wostl et al., 2008; Schuman, 2011; Lamond et al., 2011). Floods in the urban areas can also result from sewer system insufficiency (Becciu & Raimondi, 2014). Climate change also leads to an increase in flooding risk, due to hydrological alterations, including warming seas, changing patterns of precipitation and rising sea levels can also lead to flood risk increase (Singh, 2012).

The EM-DAT public database registered 5621 floods from 1900 to 2019, with the Asian continent being the most affected with 42% of the registered flood events and 98% of the total deaths, where the six first events on the total deaths ranking took place in China. In the last ten years, from 2010 to 2019, 179 flood disasters were registered, with a total of US$ 395,342,939 of estimated total damages, affecting a total of 697,227,310 people and causing 60,722 deaths (EM-DAT, 2020).

Hazard and risk assessment is an essential issue in the reduction of adverse effects of extreme events. The term "hazard" refers to the occurrence probability of a potentially damaging event, while the term "risk" refers to the extent of consequential damages and losses (Eslamian et al., 2021). Risk is generally expressed as a function of hazard and usually also of other two factors: exposure, which represents the potential loss in terms of human lives and other valuable elements, and vulnerability which represents the lack of resistance to the damaging event. Several procedures, less or more detailed, are available in the scientific literature for the assessment of these components, in most cases designed to achieve maps or charts from the combination of probabilistic analysis, historical records and geographic information knowledge (Rausand, 2013). In many countries, standard procedures are also available, mainly for planning purposes. An example is the EU Flood Directive 2007/60/EC (EC, 2007), which gives a framework for the assessment and management of flood hazards and risks.

In this chapter, an introduction to risk and hazard assessment is presented, with particular reference to flood disasters.

2 Assessment of Hazards

A proper assessment of hydrological hazards requires the reference to a watershed, especially when the effects of runoff are of concern. In most cases flood hazard can be assessed in terms of probability of flooding, that is estimating the probability that flow rates become higher than the conveyance of the drainage system. However, when the extent of flooding and/or the water depths are to be estimated, other characteristics of the flood than just flow peak are to be considered, such as flood volume and duration, time to peak, number of peaks, and, more in general, hydrograph shape.

Joint modeling of the rainfall stochastic process and the rainfall-runoff transformation is needed for the flood hazard assessment. Continuous simulation of runoff, flow rates, and water depths in the drainage network can be performed for this purpose, from long series of rainfall events, either recorded in the past or synthetically generated by Monte-Carlo methods (Kottegoda, 1980). A possible alternative is a semi-probabilistic approach (Eagleson, 1972; Adams & Papa, 2000). This approach mainly relies on the coupling of probabilistic analysis of functions of random variables and deterministic models of hydrological processes. When the semi-probabilistic approach is considered for hazard assessment, rainfall events and hydrological processes must be described in terms of conceptual models, random variables, and deterministic parameters. To overcome the correlation among variables, copula functions can be used (Salvadori et al., 2007), although independence is often assumed.

2.1 Hydrological Events and Random Variables

The rainfall stochastic process is defined as a sequence of non-zero rainfall events and dry periods (Fig. 7.1). The number of events and the amount of rainfall (rainfall depth) can vary according to the minimum dry time interval that is assumed to consider independent events.

Probabilistic analysis of hydrologic processes is often performed under the following hypotheses: (Adams & Papa, 2000):

- Stationarity of rainfall stochastic process.
- Independent rainfall events.
- Statistically homogeneous rainfall characteristics (i.e., each drawn from the same population).
- Large sample size, enough to warrant the reliable fitting of probability distributions.

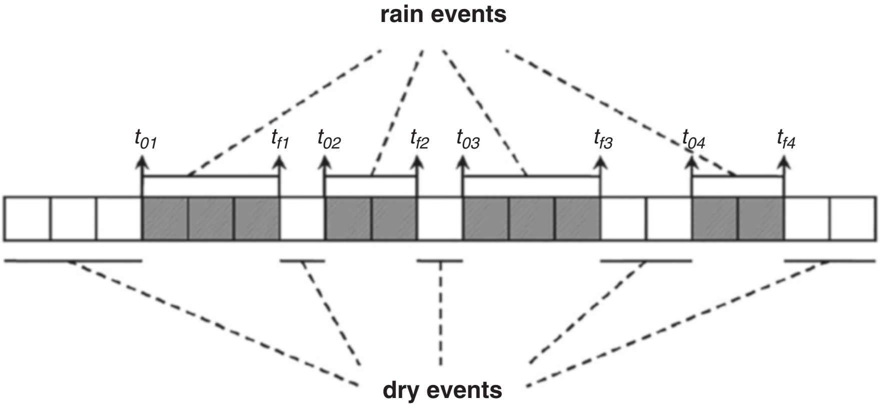


Fig. 7.1 Definition of rain and dry events. (From Garcia-Marin et al., 2008)

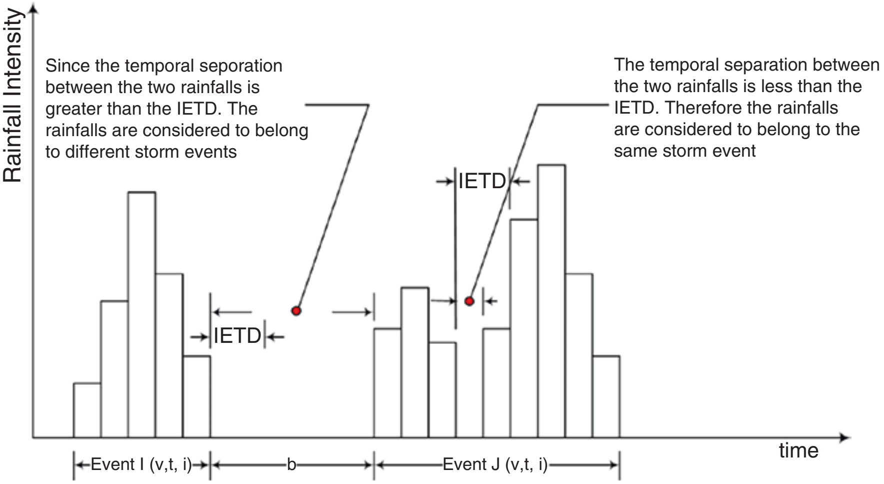


Fig. 7.2 Inter event time definition, IETD. (From Joo et al., 2014)

A minimum interevent time, called Inter Event Time Definition (IETD), is used to identify independent rainfall events in a series of records (USEPA, 1986; Bonta & Rao, 1988; Bonta, 2001; Huff, 1967; Wenzel & Voorhees, 1981). If the interevent time is smaller than IETD, the two events are joined into a single event, with depth equal to the sum of depths and duration equal to the sum of durations plus the interevent time. Otherwise, they are assumed independent (Fig. 7.2). IETD values can range from 3 min to 24 h, though values of 6–8 h are usually adopted. Improper identification of the independent events may alter rainfall statistics, leading to wrong design and analysis (Adams et al., 1986).

To select the IETD, autocorrelation analysis (Restrepo-Posada & Eagleson, 1982; Grace & Eagleson, 1967; Sariahmed & Kisiel, 1968) and coefficient of variation analysis (Nix, 1994) were often used. Lee and Kim (2018) compared the PDFs of continuous rainfall events with the confidence range of the regression curve generated from the exponential distribution for different IETD values. Joo et al. (2014) proposed a method for the assessment of IETD that considers watershed characteristics and defines IETD as the time from the end of a rainfall event to the end of direct runoff; to ensure a one-to-one correspondence between rainfall and runoff events, IETD should be greater than the watershed time of concentration. A shorter IETD must be kept for small urban watersheds, with small concentration times, while for large rural watersheds IETD can be of several hours (Adam & Papa, 2000). In literature, also other criteria, different from IETD, were proposed to identify independent rainfall events. They include:

- A minimum rainfall depth (Ziegler et al., 2006; Balme et al., 2006; Vernimmen et al., 2007).
- A minimum rainfall duration (Cutrim et al., 2000; Formis et al., 2005).
- A minimum rainfall rate for a period within the event (Fornis et al., 2005).
- A minimum rainfall rate to identify the beginning and the end of storm events (Powell et al., 2007).

Balme et al. (2006) proposed the joint use of different criteria, including IETD, minimum duration, and minimum rain depth.

The main random variables involved in hydrological processes are rainfall depth, rainfall duration, rainfall intensity, and inter-event time. Rainfall variables are recorded at discrete time intervals, (minutes, hours, days), depending on gauging devices, and can be transformed on different time scales, according to the aim of the study. The daily scale is frequently used for hydrological analyses (Kou et al., 2007; Xie et al., 2016; Yin et al., 2015; Goswami et al., 2006), although this choice may limit a detailed statistical analysis of rainfall characteristics (Wang et al., 2019). Event-scale rainfall data are often required in studies on the hydrological effects of rainfall (Renard et al., 1997; USDA-ARS, 2013; Wischmeier, 1959).

2.2 Probability of Events and Distribution Functions of Hydrological Random Variables

Several studies on different watersheds concluded that rainfall variables can be considered exponentially distributed (Chow; 1964; Eagleson, 1972, 1978; Bedient & Huber, 1992; Howard, 1976; Chan & Bras, 1979; Adams & Bontje, 1984; Adams et al., 1986; Wanielista & Yousef 1993). This assumption is often accepted to reduce the computational complexity in semi-probabilistic approaches. Considering Italian watersheds, for example, the assumption of exponential PDFs is suitable for rainfall duration but is not fully satisfied for rainfall depth and inter-event time (Becciu & Raimondi, 2015a, b). Bacchi et al. (2008) verified that for most Italian watersheds the Weibull PDF is a better choice, giving a better fitting to the frequency distribution function. Becciu and Raimondi (2012) suggested the use of the double-exponential PDF, which showed to be proper for rainfall records in Milano (Italy). Studies on rainfall data recorded in Toronto (Adams & Papa, 2000) showed that, for specific locations, Gamma PDF better fits histograms, especially for rainfall depth and inter-event time; for the duration, the two PDFs are very similar, while for rainfall intensity the exponential PDF ensures a better fitting.

The use of such distributions, however, entails more complex mathematical models than exponential PDFs. If hydrological variables are assumed as exponentially distributed, their PDFs result:

$$f_h = \xi \bullet e^{-\xi \bullet h} \tag{7.1}$$

$$f_\theta = \lambda \bullet e^{-\lambda \bullet \theta} \tag{7.2}$$

$$f_d = \psi \bullet e^{-\psi \bullet (d - \mathrm{IETD})} \tag{7.3}$$

where h, θ, and d are respectively rainfall depth, rainfall duration, and inter-event time; ξ, λ, and ψ are parameters equal to the reciprocals of their average values. The sum of rainfall depths is generally considered a Gamma PDF (Raimondi & Becciu, 2014). For more simplicity, an exponential PDF can be also assumed for the sum of two random variables with exponential distribution (Becciu and Raimondi (2015a, b).

If rainfall duration is much smaller than inter-event time and it is assumed that inter-event time has an exponential distribution, a Poisson stochastic process can be assumed (Restrepo-Posada & Eagleson, 1982; Rodriguez-Iturbe et al., 1987; Edient & Huber 1992) and the PDF of the number of storm events in a defined period is:

$$f_N = \frac{M^N \bullet e^{-M}}{M!} \tag{7.4}$$

where N is the number of independent events in the period and M is the mean of N.

2.3 Correlation Among Hydrological Random Variables

Correlation among rainfall variables is negligible except for the correlation between rainfall duration and rainfall depth (Adam & Papa, 2000; Raimondi & Becciu, 2017). Figure 7.3 reports the correlation among rainfall variables measured at the Milano-Monviso rain gauge station in the period 1971–2005. While the correlation between inter-event time and rainfall depth and between inter-event time and rainfall duration is negligible, the correlation between rainfall depth and duration is quite high.

To properly consider the correlation between rainfall depth and rainfall duration, a joint distribution should be used. Although classic inference techniques can be

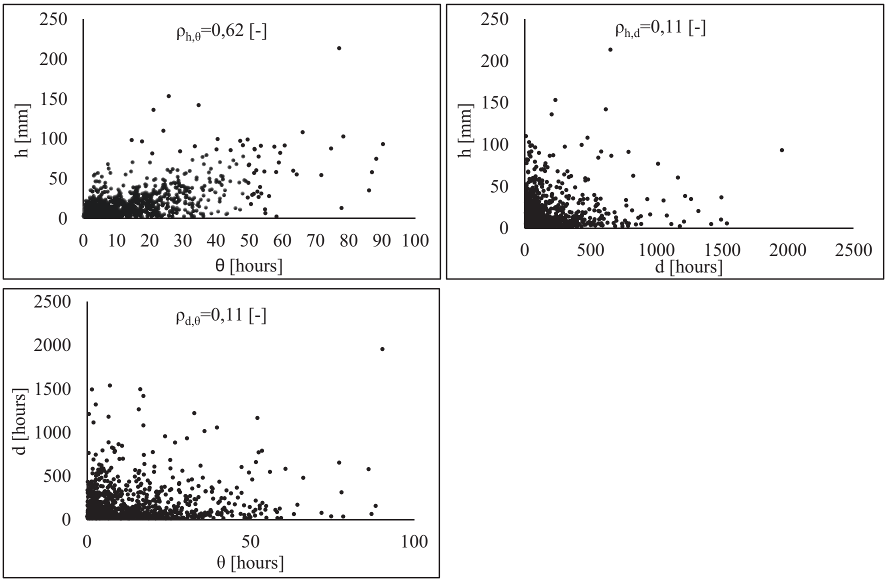


Fig. 7.3 Correlation among hydrological variables. (Milano-Monviso station, 1971–2005)

used to assess multivariate joint distribution functions, they can lead to unsatisfactory results. A significant improvement can be obtained using copulas (Joe, 1997; Nelsen, 2006; Balistrocchi & Bacchi, 2011). With this approach, the joint distribution functions can be developed from different marginal distributions. For example, in Italy, a Gumbel copula with Weibull marginal distributions seems the most appropriate (Bacchi et al., 2008; Balistricchi & Bacchi, 2011).

2.4 Conditional Probability

A fundamental variable for hydrological hazards assessment is surface flow (*I*). Considering a runoff coefficient (*f*) of the runoff surface area (*A*) and an initial abstraction (*IA*), it results:

$$I = \begin{cases} j \cdot A \cdot (h - IA) & \text{if } h > IA \\ 0 & \text{if } h \le IA \end{cases} \tag{7.5}$$

The randomness of surface flow depends mainly on the natural variability of rainfall depth; the term $(h - IA)$ is defined as net rainfall depth (h_n):

$$h_n = \begin{cases} h - IA & \text{if } h > IA \\ 0 & \text{if } h \le IA \end{cases} \tag{7.6}$$

It is a non-negative continuous random variable which PDF can be derived from that of h (Benjamin & Cornell, 1970):

$$f_{h_n}\left(x\right)=f_{h/[h>IA]}\left(x+IA\right)=\frac{f_h\left(x+IA\right)}{1-F_h\left(IA\right)}\quad x>0;h>IA \tag{7.7}$$

where F_h is the cumulative density function (CDF) of rainfall depth h. Neglecting the uncertainty of runoff coefficient and runoff surface area, the PDF of surface flow results (Becciu et al., 2018b):

$$f_I\left(x\right)=\frac{1}{\varphi\bullet A}\bullet f_{h_n}\left(\frac{x}{\varphi\bullet A}\right)=\frac{1}{\varphi\bullet A}\bullet\frac{f_h\left(\frac{x}{\varphi\bullet A}+IA\right)}{1-F_h\left(IA\right)}\quad x>0;h>IA \tag{7.8}$$

Once defined the surface flow, Guo and Adams (1998) derived the peak discharge rate PDF, by means of conditional probability. Semi-probabilistic approaches were also used to assess different characteristics of runoff processes and evaluate the performance and reliability of structures for stormwater control, such as stormwater detention facilities and sustainable urban drainage systems, SUDSs (Raimondi & Becciu, 2014a, b, 2015, 2020; Raimondi et al. 2020a, b).

2.5 Trend and Autocorrelation in Stochastic Processes

Hydrological processes are ruled by complex interrelations among different kinds of natural dynamic phenomena. The series of hydrological variables, therefore, are often recognized as affected by both trends and autocorrelations. These features of the stochastic processes are particularly common in runoff series. Although several well-known techniques are available to consider these features, it is often convenient to perform the probabilistic analysis of hydrological variables under the simpler hypotheses of stationarity and stochastic independence (Kottegoda, 1980, Adams & Papa, 2000). This simplification is justified by the weak autocorrelation and trend that are observed in many cases.

3 Assessment of Risks

A very general definition of risk assessment was given by the American Association of Safety Engineers (ANSI/ASSE, 2011; Manuele, 2016): “Risk assessment is that part of risk management which provides a structured process that identifies how objectives may be affected and analyses the risk in term of consequences and their probabilities before deciding on whether further treatment is required. Risk assessment attempts to answer the following fundamental questions:

- What can happen and why (by risk identification)?
- Which are the consequences?
- What is the probability of future occurrence?
- Are there any factors that mitigate the consequence or that reduce the hazard?
- Is the level of risk tolerable or acceptable and does it require further mitigation actions?"

A similar general definition was given by the American Society of Safety Professionals (ASSP, 2019): "risk assessment serves many purposes for any organization, including reducing operational risks, improving safety performance, and achieving objectives. While many individuals are involved in the process and many factors come into play, performing an effective risk assessment comes down to three core elements: risk identification, risk analysis, and risk evaluation".

The first step required is then the risk identification. According to the ISO 31000-2018 standard, the following factors should be addressed by safety professionals and stakeholders:

- Tangible and intangible sources of risk.
- Threats and opportunities.
- Causes and events.
- Consequences and their impact on objectives.
- Limitations of knowledge and reliability of the information.
- Vulnerabilities and capabilities.
- Changes in external and internal context.
- Indicators of emerging risks.
- Time-related factors.
- Biases, assumptions, and beliefs of those involved.

Risk assessment matrices can be used to compare hazards and prioritize actions. Classifying risks, based on the probability and extent of a potentially damaging event, and placing them on a matrix or a map allows for determining the highest risk levels to address.

The second step is then the risk analysis, where the information obtained through risk identification can be used to analyze the risk level for each hazard and define actions according to a chosen criterion, for example, based on existing controls.

As specified by Rausand (2013), risk analysis must provide answers to these three needs:

(a) Hazard identification, which means not only identifying which are the hazards and the threats, but also the people and the assets that may be armed.
(b) Frequency analysis, with the identification of the causes of dangerous events, also based on experience and/or expert judgment.
(c) Consequence analysis, with an inductive analysis to identify all the potential final consequences, both direct and indirect.

Risk analysis may be performed either in a qualitative or quantitative way, depending on the object of the analysis. In the first case, both probabilities and consequences are evaluated in an empirical way. In the second, numerical estimates are performed, often along with associated uncertainties.

- Qualitative risk analysis is a risk analysis where probabilities and consequences are determined purely qualitatively.
- Quantitative risk analysis is a risk analysis that provides numerical estimates for probabilities and/or consequences, sometimes also with associated uncertainties.

Risk evaluation is the third and final step of risk assessment. It strictly depends on three main factors: hazard, which is the probability of occurrence of the threatening event, exposure, which represents the potential losses in terms of human lives and other valuable elements, and vulnerability, which represents the lack of resistance to damaging or destructive forces.

According to Kottegoda and Rosso (2008), the risk that a system does not meet the demand can be defined as the probability of failure p_f over the system's lifetime. This probability depends on the system operating conditions. System reliability, which can be denoted as r, is the complementary probability of non-failure, that is $r = 1 - p_f$.

It is worth to highlight that the definition of failure must be related not only to the collapse or to the complete loss of functionality of a system, but also to a reduced capacity to respond to project requirements or to meet users' demands. For example, a catastrophic flood that exceeds the design value may cause the break of a dam, but also only partial damages that, maybe together with a poor design, may cause low performance in the future use of water resources. Although engineers are primarily asked for the assurance of system performance and safety, economic and social constraints influence the acceptable levels of risk. Therefore, an accurate cost-benefit and environmental analysis must be performed before planning and designing an engineering system.

The simpler and most effective approach, especially in natural disaster analysis, is to define the risk as the combination of the probability of a potentially dangerous event and its adverse consequences (Kron, 2002; Bignami et al., 2019). Without damages or losses of any kind, there is no risk, whatever the importance or the level of the potential danger of an event is. Similarly, an event is considered a catastrophe when damages and losses are huge.

So, the probability of a potentially dangerous event (hazard) has to be combined with the number of values in the area in which effects are expected (exposure), as well as their susceptibility to losses (vulnerability). Hence, the risk can be expressed as a function of these three quantities.

All the factors that determine risks are variable. Although the occurrence and the intensity of threatening natural phenomena are beyond human control capacity, their effects can be mitigated through proper measures. For instance, for a given rainfall event, the hazard related to the consequent flood volume and peak flow downstream a watershed can be reduced by regulations on land use, agricultural practices, and defense works. In addition, the exposure can be controlled by avoiding hazard-prone areas and settlements. Moreover, increasing the structural and water resistance of buildings and infrastructures reduces vulnerability.

The usual approaches analyze these factors (i.e., hazard, vulnerability, and exposure) separately, merging results empirically, with the major aim of just ranking the risk levels. This implies that the three factors are assumed to be mutually independent, without considering their mutual relations. Although this approach is simpler and can be useful in most cases, it can cause significant bias in risk evaluation and also on real effects of mitigation measures in more complex scenarios (Danielsson & Zhou, 2016).

However, taking into account these interactions requires complex analysis, and achieving a proper insight into the mechanisms and feedback involved, independently of the kind of deterministic or stochastic methods adopted, is generally difficult. For instance, considering the flood risk there is a need for merging knowledge from hydrology and social sciences (Sivapalan et al., 2012; Di Baldassarre et al., 2015; Gober & Wheater, 2015) and/or ecology and hydrology (Eagleson, 2002; D'Odorico & Porporato, 2006; Good et al., 2015).

Particularly, it is enough clear that vulnerability to natural disasters is mostly linked to the country's development level and also to the quality of its environment (Peduzzi et al., 2009). Different degrees of vulnerability are observed in different social groups in both developed countries (Cutter & Finch, 2008; Fekete, 2009; Dzialek et al., 2016) and developing ones (Adger, 2006; Rasch, 2015; Salami et al., 2017).

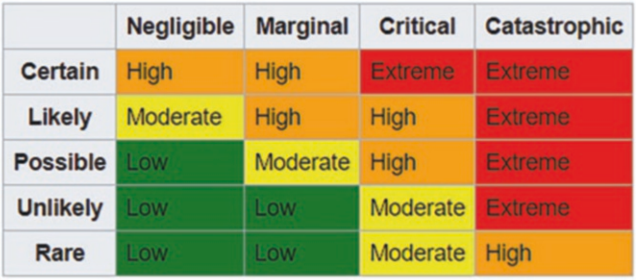
A risk matrix can be used for risk assessment, merging the probability of the event and the severity of its consequences. This is a simple approach, useful in decision-making. Although standard risk matrices were proposed to be used in certain contexts (e.g., ISO, 2018), general matrices can be developed. For example, the consequences in terms of life losses (Severity) can be categorized as:

- Catastrophic or fatal, in case of multiple deaths.
- Critical or major, in case of one death or multiple severe injuries.
- Marginal or moderate or minor, in case of one severe injury or multiple minor injuries.
- Negligible or trivial, in case of one minor injury.

The probability (likelihood) of an harmful event might be categorized as "certain", "likely", "possible", "unlikely", and "rare" or "remote". The resulting risk matrix could be qualitative (Fig. 7.4), quantitative (Fig. 7.5), or a mix (Fig. 7.6):

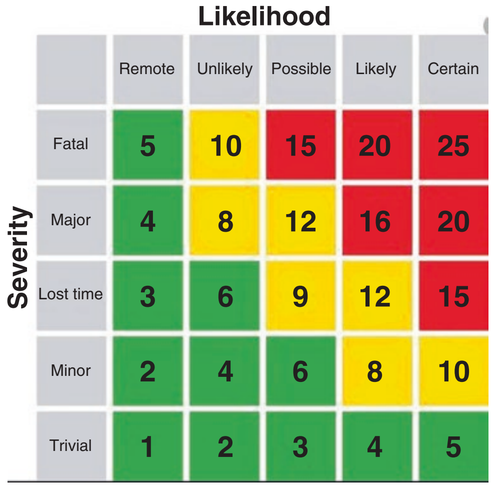
Risk matrices allow the estimation of different levels of risk associated with different events. Although a risk matrix is a very powerful tool, it has some limits (Cox, 2008):

- Poor resolution. Typical risk matrices can correctly and unambiguously compare only a small fraction (e.g., less than 10%) of randomly selected pairs of hazards. They can assign identical ratings to quantitatively very different risks ("range compression").



	Negligible	Marginal	Critical	Catastrophic
Certain	High	High	Extreme	Extreme
Likely	Moderate	High	High	Extreme
Possible	Low	Moderate	High	Extreme
Unlikely	Low	Low	Moderate	Extreme
Rare	Low	Low	Moderate	High

Fig. 7.4 Example of a qualitative risk matrix



Likelihood

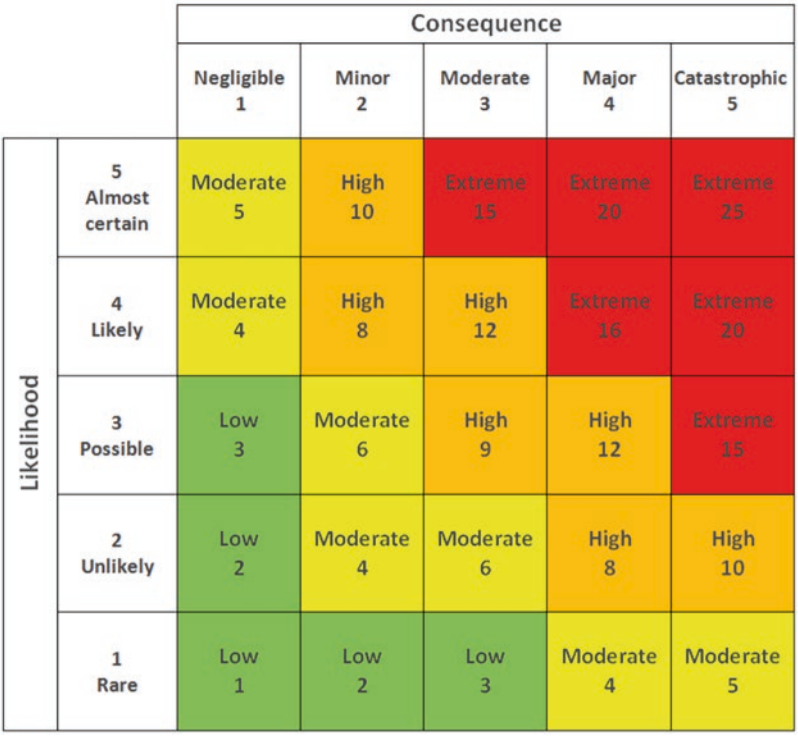
Severity

	Remote	Unlikely	Possible	Likely	Certain
Fatal	5	10	15	20	25
Major	4	8	12	16	20
Lost time	3	6	9	12	15
Minor	2	4	6	8	10
Trivial	1	2	3	4	5

Fig. 7.5 Example of a quantitative risk matrix

- Errors. Risk matrices can mistakenly assign higher qualitative ratings to quantitatively smaller risks. For risks with negatively correlated frequencies and severities, they can be "worse than useless", leading to worse-than-random decisions.
- Suboptimal resource allocation. Effective allocation of resources to risk-reducing countermeasures cannot be based on the categories provided by risk matrices.
- Ambiguous inputs and outputs. Categorizations of severity cannot be made objectively for uncertain consequences. Inputs to risk matrices (e.g., frequency and severity categorizations) and resulting outputs (i.e., risk ratings) require subjective interpretation, and different users may obtain opposite ratings of the same quantitative risks. These limitations suggest that risk matrices should be used with caution, and only with careful explanations of embedded judgments.

The most significant limitation is that risk matrices can give an arbitrary risk ranking (Thomas et al., 2014). The design of the matrix, such as the way likelihood and severity are classed, may influence risk rankings.



		Consequence				
		Negligible 1	Minor 2	Moderate 3	Major 4	Catastrophic 5
Likelihood	5 Almost certain	Moderate 5	High 10	Extreme 15	Extreme 20	Extreme 25
	4 Likely	Moderate 4	High 8	High 12	Extreme 16	Extreme 20
	3 Possible	Low 3	Moderate 6	High 9	High 12	Extreme 15
	2 Unlikely	Low 2	Moderate 4	Moderate 6	High 8	High 10
	1 Rare	Low 1	Low 2	Low 3	Moderate 4	Moderate 5

Fig. 7.6 Example of a qualitative and quantitative risk matrix

Risk communication is another important issue, and it must be indeed a further fourth element of the risk assessment process, threaded throughout all the already mentioned three steps and equally crucial to effective risk management. Results of risk identification, analysis, and evaluation must be communicated to all the stakeholders to provide a proper understanding and evaluation of possible mitigation actions. Particularly, the population should be aware of the risks in their area and how to behave in case of an extreme event. Finally, it must be stressed the importance to clarify the criteria on which risks are managed and correlating them to the consequent actions, also implementing the proper monitoring tools for risk management (Ranke, 2016).

3.1 Risk

As already mentioned, three components determine the risk, R:

1. Hazard, H, represents the threatening natural event in terms of its probability of occurrence.
2. Exposure, E, represents the human lives and the other values that are involved.

3. Vulnerability, V, represents the lack of resistance to damaging (or destructive) events.

While hazard H is definitively a probabilistic quantity, given a chosen average return interval (ARI) and a probability distribution of the random variables characterizing the event, apparently vulnerability V and exposure E are deterministic quantities. But, indeed, also these last two are subject to relevant uncertainties and their values could vary according to several factors (e.g., in the case of flood risk analysis: peak flow rate, flood volume, initial conditions in the area, etc.).

A formal probabilistic approach, that is far too complex for most of the practical applications, is:

$$R = R(H,E,V) = \iiint p(H,E,V) \cdot \mathrm{d}H \cdot \mathrm{d}E \cdot \mathrm{d}V \tag{7.9}$$

where p (H, E, V) is the joint probability density function of H, E, and V.

In its simpler form, the risk is computed just by multiplying the three components:

$$R = H \bullet E \bullet V \tag{7.10}$$

Indeed, for any approach, it is generally quite difficult to attribute proper values to these three parameters, especially to E and V. Nevertheless, exposure E and vulnerability V can be combined to form a quantity C representing the consequences resulting from a single event with an occurrence probability P (Kron, 2002):

$$R = P \bullet C \tag{7.11}$$

Very often, however, disasters (especially the natural ones) do not present themselves just in the form of one single event, with a given probability of occurrence, but in many different forms, with different possible outcome values which can be even infinite. A typical situation of this kind is the risk created by flood discharges Q:

$$R = \int_{\infty}^{Qa} C(Q) \bullet p(Q) \bullet \mathrm{d}Q \tag{7.12}$$

where:

$C(Q)$: costs of the losses caused by a given discharge rate Q;
$p(Q)$: probability density function of the discharge Q;
Qa: flood value above which losses start to occur.

In general, integration cannot be carried out analytically, except for combinations of $C(Q)$ and $p(Q)$ originating simple mathematical expressions of the quantity $C(Q) \cdot p(Q)$.

3.2 Hazard

Hazard H is the probability that a potentially damaging event, which may harm people, economic assets, infrastructure, environment, and so on, will occur in a given period and in a given place. The possible values of H range from 0 (impossible event) to 1 (certain event). If the potentially damaging event is characterized as a quantity with a variable intensity I, then hazard H can be expressed as $H = H(I)$. In hydrology, a typical example is the hazard of flooding, where the characterizing quantity is the flood peak flow Q and therefore the hazard can be expressed as $H = H(Q)$. A detailed discussion of the probability distribution functions suitable for hazard description has been discussed in Sect. 2.2.

3.3 Exposure

Exposure E is a measure of the importance of the elements exposed to the damaging event. It can be expressed either in terms of money, using other dimensional indicators, or with dimensionless values ranging from 0 (no value) to 1 (invaluable). The use of a range between 0 and 1 is suitable especially when the aim of risk analysis is just to define a heuristic risk ranking of the considered threats. If the potentially damaging event is characterized as a quantity with a variable intensity I, then the exposure E can be expressed as $E = E(I, G)$, where G summarizes the group of elements that can be affected. Table 7.1 shows an example of the main factors and related indicators of exposure for, respectively, structures, population, and economy.

3.4 Vulnerability

Vulnerability V is a measure of the weakness in front of a possibly damaging event of human communities, structures, infrastructures, services, and environments in a risk-prone area that are likely to be damaged or disrupted, on account of their nature or location (Wanga et al., 2012). It is also related, especially considering also

Table 7.1 Example of main factors and related indicators of exposure

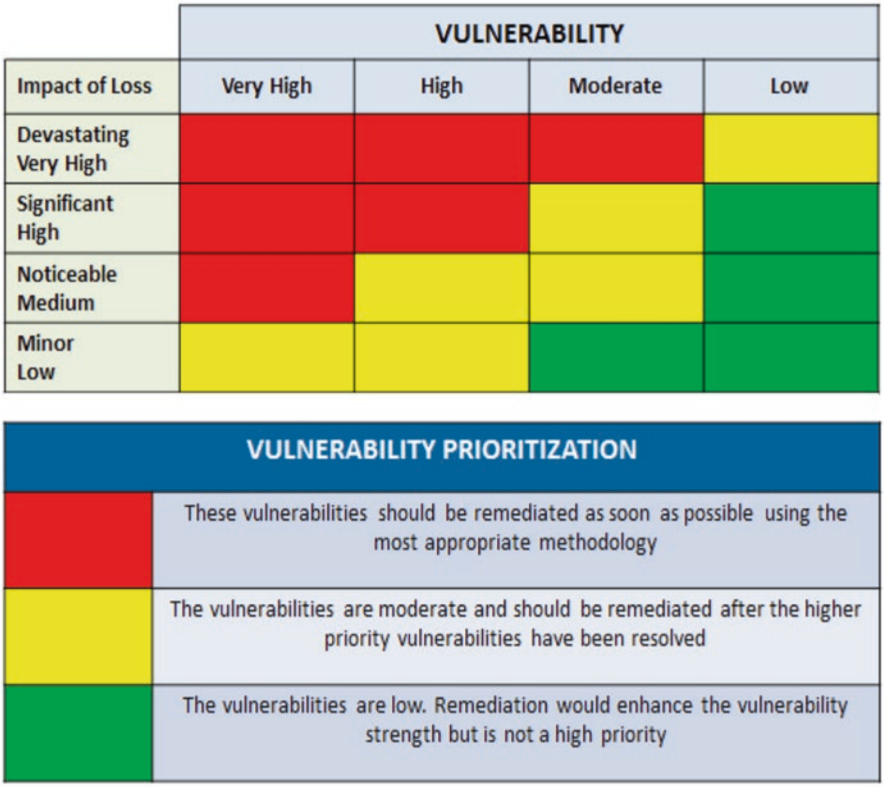
Main factor	Indicator name	Indicator
Structures	(E1) Number of housing units	Number of housing units (living quarters)
	(E2) Lifelines	Percentage of homes with piped drinking water
Economy	(E3) Total resident population	Total resident population
Population	(E4) Local gross domestic product (GDP)	Total locally generated GDP in constant currency

Bollin and Hidajat (2006), UNU-IEHS and NNSUACE (2006) climate change, to the lack of resilience of the exposed element or system to cope with and adapt to dangerous events (Cardona et al., 2012). The numerical values of the vulnerability are dimensionless and range between 0 (no damage) to 1 (destruction).

In general, if the potentially damaging event is characterized as a quantity with a variable intensity *I*, then vulnerability *V* can be expressed as $V = V(I, G)$, where *G* summarizes the group of elements that can be affected.

As summarized by Fuchs et al. (2012) and Papathoma-Köhle (2016), vulnerability matrices (Sage, 2005; Islam & Ryan, 2016), vulnerability curves (Papathoma-Köhle et al., 2012, 2017; Papathoma-Köhle, 2016), and vulnerability indicators (Bollin and Hidajat, 2006; UNU-IEHS and NNSUACE, 2006; De Ruiter et al., 2017) are most commonly used for assessing physical vulnerability.

For example, Fig. 7.7 shows a Typical Vulnerability Risk Matrix and related Vulnerability Prioritization Scale (Sage, 2005), while Fig. 7.8 shows an example of different vulnerability curves fitting the experimental data of the case study of Martell Valley, South Tyrol (Papathoma-Köhle et al., 2012), and Table 7.2 shows an



	VULNERABILITY			
Impact of Loss	Very High	High	Moderate	Low
Devastating Very High	🟥	🟥	🟥	🟨
Significant High	🟥	🟥	🟨	🟩
Noticeable Medium	🟥	🟨	🟨	🟩
Minor Low	🟨	🟨	🟩	🟩

VULNERABILITY PRIORITIZATION	
🟥	These vulnerabilities should be remediated as soon as possible using the most appropriate methodology
🟨	The vulnerabilities are moderate and should be remediated after the higher priority vulnerabilities have been resolved
🟩	The vulnerabilities are low. Remediation would enhance the vulnerability strength but is not a high priority

Fig. 7.7 Typical vulnerability risk matrix and related vulnerability prioritization scale. (From Sage 2005)

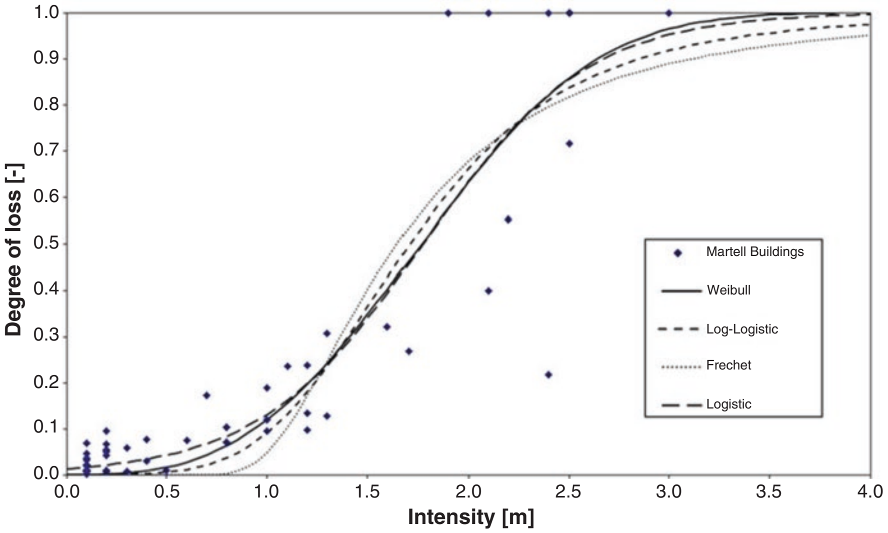


Fig. 7.8 Relationship of the degree of loss for buildings in the Martell Valley, South Tyrol, and the debris flow intensity expressed as deposition height. (Papathoma-Köhle et al., 2012)

Table 7.2 Example of main factors and related indicators of vulnerability

Main factor	Indicator name	Indicator
Physical/ Demographic	(V1) Density	People per km^2
	(V2) Demographic pressure	Population growth rate
	(V3) Unsafe settlements	Homes in hazard-prone areas (ravines, river banks, etc.)
	(V4) Access to basic services	Percentage of homes with piped drinking water
Social	(V5) Poverty level	Percentage of population below poverty level
	(V6) Literacy rate	Percentage of adult population that can read and write
	(V7) Attitude	Priority of population to protect against a hazard
	(V8) Decentralization	Portion of self-generated revenues of the total budget
	(V9) Community participation	Percentage of voter turnout at last municipal elections
Economic	(V10) Local resource base	Total available local budget in US$
	(V11) Diversification	Economic sector mix for employment
	(V12) Small business	Percentage of business with fewer than 20 employees
	(V13) Accessibility	Number of interruptions of road access in the last 30 years
Environmental	(V14) Area under forest	Percentage of the municipality area covered with forest
	(V15) Degraded land	Percentage of the area that is degraded/ eroded/desertified
	(V16) Overused land	Percentage of agricultural land that is overused

From Bollin and Hidajat (2006), UNU-IEHS and NNSUACE (2006) example of main factors and related indicators of vulnerability (Bollin & Hidajat, 2006; UNU-IEHS and NNSUACE, 2006).

4 Case Studies

4.1 Seveso River in Milano, Italy

The Seveso river is a small stream flowing from North toward the city of Milano (45°29′10″ N, 9°12′13″ E). The Seveso watershed, when reaches Milano metropolitan area, has approximately 226 km^2 area, of which about 100 km^2 is highly urbanized. The river flows across the city of Milano in an underground channel for about 7 km, before merging into the river Lambro in the south. Although is considered a minor river in Italy, the Seveso is well known for the frequent flooding and resulting damages to the city of Milano. In the last 140 years, more than 340 floods (i.e., 2.4 per year) were registered, of which about 110 since 1976. To reduce the frequency of flood events, a by-pass channel (called CSNO) was built in the 1980s of twentieth century before the river reaches the city, to divert part of the flow to the river Ticino. Although this measure seemed to be effective at first, after a few years, with the growing urbanization, the efficiency became negligible and a new plan for large detention reservoirs was prepared and is currently in construction (Becciu et al., 2018a). Hydraulic-hydrologic modeling was used to assess flood risk in the city of Milano from the Seveso river watershed. The assessment framework was based on the joint estimation of hydrological hazard, expressed in terms of critical rainfall intensity probability (i.e., corresponding to peak discharges over the underground channel hydraulic conveyance), and of vulnerability, expressed in terms of flooded urban area extension. According to Italian regulations, in compliance with EU Flood Directive 2007/60/EC, the hazard is classified into three classes, from P1 (Low) to P3 (High) (Table 7.3). The vulnerability is classified into four classes, expressed in terms of the degree of damages, from D1 (Low) to D4 (Very High) (Table 7.4).

Combining hazard and vulnerability, the risk is classified into four classes, from R1 (low) to R4 (very high) (Table 7.5).

Figure 7.9 shows the hazard and risk map of the north area of Milano, where the R4 area is highlighted, meaning the area with class hazard P3, meaning a high

Table 7.3 Classification of flooding hazards

Class of hazard	Probability of flooding	ARI [years]
P1	Low	200 ÷ 500
P2	Medium	100 ÷ 200
P3	High	20 ÷ 50

Table 7.4 Classification of vulnerability to flooding

Class of vulnerability	Damage	Type of area and effects
D1	Low	Non-urbanized, free of manufacturing activity
D2	Medium	Minor infrastructures and manufacturing activities. Limited effects on people and economy.
D3	High	Risk for people and economy. Major manufacturing activities and lifelines.
D4	Very High	Risk of life losses. Relevant damages to buildings, infrastructures, heritage, economy, and environment.

Table 7.5 Classification of flooding risks

Class of risk		Class of hazard		
		P1	P2	P3
Class of Vulnerability	D1	R1	R1	R1
	D2	R1	R2	R3
	D3	R2	R3	R4
	D4	R2	R4	R4

probability of flooding for an ARI of 20–50 years, and vulnerability D4, meaning a very high risk of life losses and property damages. Risk mitigation measures to reduce floods considering 100 years ARI would require the implementation of at least five retention reservoirs with an estimated cost of around 130 million Euros (Becciu et al., 2018a).

4.2 *Anhangabaú Watershed, San Paolo, Brazil*

The Anhangabaú watershed is in San Paolo (23° 33′ 0.9925″ S, 46° 38′ 29.5523″ W), the most populous city in the Americas, covering an area of approximately 5.4 km^2 with 78% impermeable surface and most of watercourses culverted. The area is frequently affected by floods, with an average of 147 registered flood events in the years 2008–2012. A risk assessment study held by FCTH (Fundação Centro Tecnológico de Hidráulica) and the San Paolo municipality provided watershed hazard and risk maps considering three risk mitigation solutions and the effect on the watershed of adopting source control measures for stormwater. The considered risk mitigation structural measures were: the implementation of two storage tanks with a total of 80,000 m^3 capacity (alternative A), a by-pass channel discharging to a downstream basin (alternative B), and the implementation of "superpipes", i.e., substituting stretches of the existing drainage system with pipes with >3 m cross-section diameter that would function as reservoirs (alternative C) (Silva et al., 2014). Hydrologic modeling was used to assess hazards by the PCSWMM package for the current scenario and three risk mitigation solutions for 100 years ARI. The existing

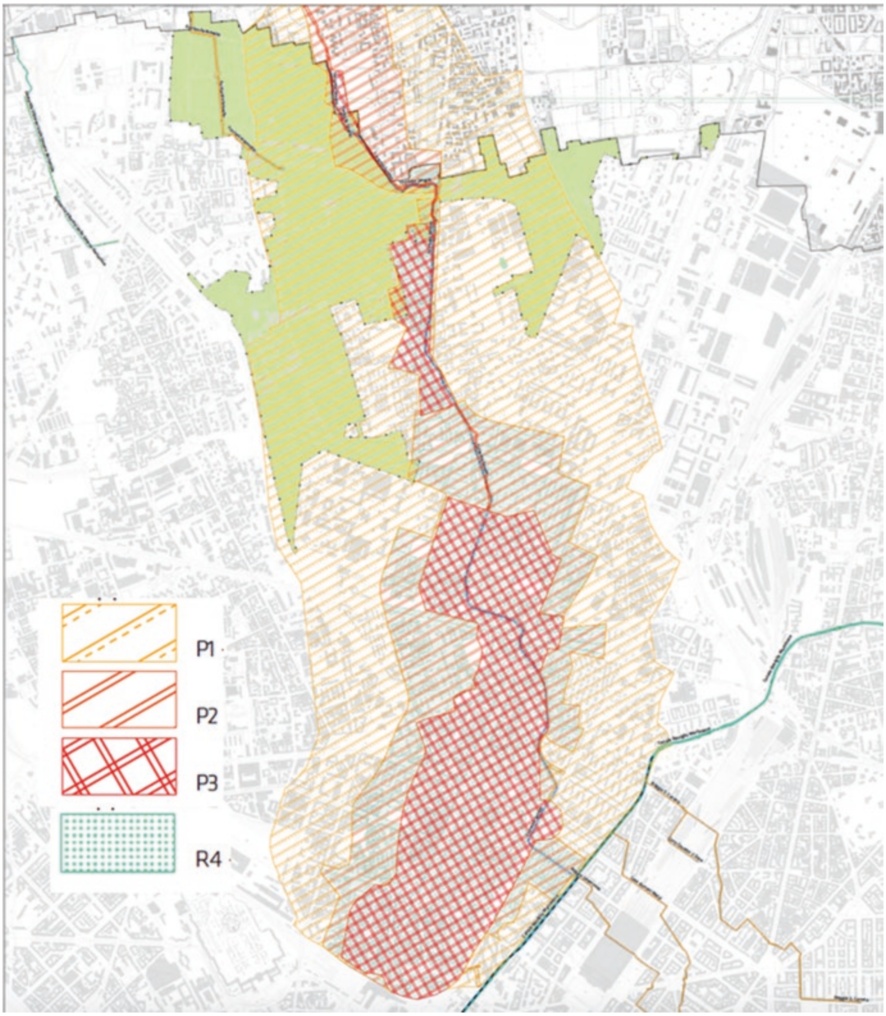


Fig. 7.9 Map of flooding hazard and risk in the north area of Milano

network considered in the model consisted of a total of 110 km of roads, 50 km of drainage network system, and 2802 nodes representing curb inlets and drainage grates (Fig. 7.10). Precipitation data were gathered in five stations within the watershed and tree rainfall-runoff events were used for model calibration (Silva et al., 2014).

Water depth can reach over 50 cm on 15% of the watershed area for a 100-year ARI, with flooding concentrating on the square Praça da Bandeira located on the floodplain where the two major streams of the watershed affluence on the Anhangabaú stream. Risk assessment in the current scenario: 21.6% of buildings are considered under high risk, 43.5% under medium risk, and 34.8% under low risk.

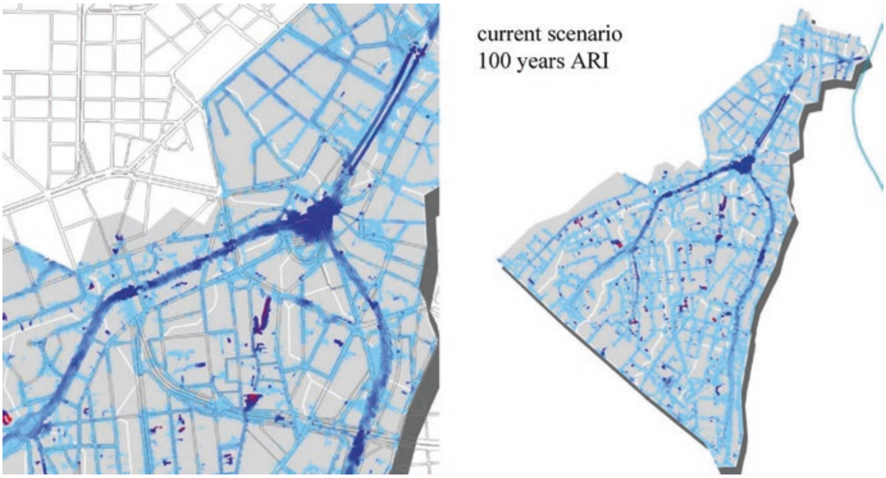


Fig. 7.10 Flooding hazard map of the Anhangabaú in current scenario for 100 years ARI; floodplain (left) and the entire watershed (right). (Silva et al., 2014)

Table 7.6 Risk level on the percent of buildings within the watershed considering different scenarios for ARI = 100 years

Risk level	Current scenario (%)	Solution A (%)	Solution B (%)	Solution C (%)
Low	34.8	35.8	37.9	48.0
Medium	43.5	45.8	45.7	44.2
High	21.6	18.4	16.4	7.8

Among the possible risk mitigation measures, the alternative C results to be the most effective, being the areas with water depth above 50 cm in case of flooding reduced to 3% of the watershed surface.

The risk assessment used the criteria in Table 7.5, which considered low risk when water depth was confined to street level, medium level when water depth reached sidewalks, and high risk when water depth reached 15 cm above sidewalks. Considering a 100-year ARI event, the risk analysis showed that 35% of buildings are under low risk, 44% under medium risk, and 22% under high risk. Solution A allows a reduction of the buildings under high risk for 100-year ARI event from 21.6% to 18.4%, solution B from 21.6% to 16.4%, and alternative C from 21.6% to 7.8% (Table 7.6).

5 Conclusions

The assessment of hazards and risks is a complex task. Indeed, all the different pieces of information have to be considered and analyzed, with uncertainties due to, among others, system evolution in time and space, weak or strong correlation among various factors, and even the lack of reliable data (Frewer et al., 2003; Rougier et al., 2013). Moreover, the random nature of meteo-climatic factors is an additional element of complexity in the evaluation of hydrologic disasters (Sahani et al., 2019).

Although well-established approaches are available from the literature for this assessment, as synthetically presented in this chapter, some current and future challenges are worth to be considered. Particularly, more research efforts should be devoted to developing conceptual and practical frameworks for the analysis of issues such as multi-hazard scenarios (Sadegh et al., 2018), infrastructure interdependency (Hickford et al., 2018; , resilience capability (Rehak et al., 2018), and fast-changing systems.

An increasing awareness must be focused on the possible combination and interrelation of hazards of different kinds, especially in densely populated areas, with particular concern for the Na-Tech (natural and technological) risks. Sometimes this condition is due to the same event, others it's due to cascade effects, in which a triggering event is at the origin of others. An example of the first case is intense rainstorms, that at the same time increase both river flows and water stage in receiving water bodies. A classic example of the second case is the earthquake that may induce landslides over river channels, with the formation of flood waves both upstream and downstream, or a chain of catastrophic events amplified by a lack of adequate prevention, like the Fukushima tsunami and consequent nuclear accident (IAEA, 2015; Synolakis & Kânoğlu, 2015).

Also, the mutual interdependency of infrastructures may lead to a possible increase in risks (Giannopoulos et al., 2012; Wang et al., 2019; C40, 2017, Heino et al., 2019). Flooding in urban areas, for example, may produce a failure of electric and data networks, with the consequent outage of control devices, such as flood gates and pumps, while intense rainstorms may damage sensors on which alert systems rely. On the other hand, current technology offers new opportunities for increasing both the real-time, space-distributed knowledge of system status and the capabilities of real-time defensive reactions.

So, more and more efforts are being made in this field, in terms of both research and technology, to fill the knowledge gaps and improve the procedures for risk assessment. Nevertheless, many open issues are still present on the stage, and current and future challenges are waiting to be accepted.

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