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NOVEL APPROACHES FOR FLOOD RISK ASSESSMENT USING EXPOSURE-VULNERABILITY MATRICES

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All’Amor, “che move il sole e l’altre stelle”.

Contents

Abstract

The classical approach to flood defence, aimed at reducing the probability of flooding through hard defences, has been substituted by flood risk management approach which accepts the idea of coping with floods and aims at reducing not only the probability of flooding, but also the consequences. In this view, the concept of vulnerability becomes central, such as the (non-structural) measures for its increment: even if it is believed their effectiveness, methods for its evaluation are rare, such as data on their effects.

On 22 November 2011, an exceptional rainstorm hit the Longano catchment (located in Northeast part of Sicily, Italy) producing local heavy rainfall and flash flooding. The flash flood involved property, buildings, roads and more than 100 commercial estates have suffered severe damages. Some days after the event, the municipality provided people forms to describe the damages that occurred on their properties. Unfortunately, the lack of common guidelines in compiling them, their coarseness and the impossibility to have monetary information on them (such us damage data from previous events), did not allow the implementation of a detailed damage analysis.

What has been developed in this work is a method for a qualitative evaluation of the consequences of floods, based on a crisscross analysis of vulnerability curves and classes of exposure for assets at risk. Vulnerability curves, derived through a synthetic approach, are defined for different building typologies, as function of the water depth, while the classes of the variable Exposure are defined in function of both their asset value and their importance for society. A GIS-based tool (using hazard information obtained from hydraulic modelling, building parcels, vulnerability curves and exposure classes) is used to collocate each element at risk inside an Exposure-Vulnerability matrix.

The construction of a E-V matrix allow both to understand the actual situation of a catchment (and the possible consequences of a flood event) and to study the effectiveness of non-structural measures for a site, just studying how their implementation modifies the distribution of elements at risk inside it. Referring directly to vulnerability (and considering its classes instead of single values) allows to estimate the possible consequences of an event even in those catchment where the lack of damage data does not allow the construction of empirical depth damage curves. The instrument proposed can be useful for authorities responsible for development and periodical review of adaptive flood risk management plans.

Sommario

L’approccio “classico” di difesa dall’inondazione, basato sulla costruzione di opere strutturali in grado di contenere piene di tempo di ritorno sempre maggiore, è stato sostituito da un approccio gestionale del rischio da inondazione, nel quale prende piede sempre più il concetto di “convivere” con la piena accettando un certo livello di inondazione. In quest’ottica, la vulnerabilità diventa la variabile chiave nell’equazione del rischio e gli interventi non strutturali lo strumento principale per mitigarlo: nonostante si creda nella loro efficacia, i metodi per stimarla sono pochi, così come scarsi sono i dati sui loro effetti.

Il 22 Novembre 20112, un evento meteorico eccezionale ha colpito il torrente Longano (situato in Sicilia nord-orientale) causando localmente piogge intense e fenomeni di flash flood. Queste ultime hanno coinvolto terreni, edifici, strade e causato danni a più di 100 immobili commerciali. Qualche giorno dopo l’evento, il Comune ha distribuito alla popolazione delle schede di rilevamento danni per raccogliere i dati relativi ai danni subiti da ciascuno. Sfortunatamente, la mancanza di indicazioni utili alla compilazione e la grossolanità delle informazioni richieste, insieme alla mancanza di dati monetari (anche raccolti a seguito di eventi precedenti), non consente l’implementazione di un’analisi di danno dettagliata.

In questo lavoro di tesi è stata proprio sviluppata una procedura per la stima qualitativa dei danni da inondazione, basata sull’utilizzo incrociato di curve di vulnerabilità e classi di esposizione associata agli elementi a rischio. Le curve di vulnerabilità sono state derivate per via sintetica, in funzione delle sole altezze di allagamento, per diverse tipologie di edificio, mentre le classi di esposizione sono state definite in funzione sia del valore di ciascun elemento, che della sua importanza

funzionale e strategica nella società. Tramite un tool sviluppato in ambiente GIS (che integra le informazioni di pericolosità e vulnerabilità) è stata calcolata la classe di vulnerabilità di ciascun elemento, collocandolo poi all'interno di una matrice Esposizione-Vulnerabilità.

L'utilizzo di una matrice Esposizione-Vulnerabilità permette non solo di fotografare l'attuale situazione di un bacino (e le possibili conseguenze di un'inondazione), ma anche di valutare l'efficacia di misure non strutturali studiando come la loro implementazione modifichi la distribuzione degli elementi al suo interno. Riferirsi direttamente alla vulnerabilità (considerandone classi di valori piuttosto che singoli valori) permette di stimare le possibili conseguenze di eventi calamitosi anche in bacini in cui la mancanza di dati di danno impedisce le derivazione per via empirica di curve di danno. Lo strumento proposto può essere utile nella redazione e nei periodici aggiornamenti di piani di gestione del rischio da inondazione.

Introduction

Flooding is a global phenomenon acknowledged by many experts as one of the most destructive. According to the UNESCO (2004), "*Floods are the most destructive type of water-related disaster. Between 1991 and 2000, more than 665 000 people died in 2557 natural disasters, 90% of which were water-related. From 1971 to 1995, floods affected more than 1.5 billion people. More than 81 million were homeless. Asia is most at risk, some 228 000 people having perished between 1987 and 1997 in floods that caused economic losses of $136 billion*".

Flooding, in fact, do not cause just economic losses, but it is responsible of a large percentage of all deaths from climate-related disasters. Ohl and Tapsell (2000) described flooding as predominate cause of death associated with natural disasters in the United States and reported that "*flooding accounts for 40% of all natural disasters worldwide and causes about half of all deaths from natural disasters. Most floods occur in developing regions and tropical regions where the impact on public health is substantial, the number of people displaced is often large, and the number of deaths is high*".

The destructive consequences of floods are increasing in many parts of the world, not only due to changes in climate, but also largely due to continuous population growth along floodplains and to changes in land use. (Milly et al., 2002; Di Baldassarre et al., 2010; Jha et al., 2012). The population growth shows as its defining feature the urban settlements' expansion. This aspect becomes more evident if we think that this fast growth makes urban settlements grow in the form of unplanned development in floodplains, in coastal and inland areas alike, as well as in other flood-prone areas.

Urban areas can be flooded by rivers, coastal floods, pluvial and ground water floods, and artificial system failures. Usually floods are the result of meteorological and hydrological extremes combined with ineffectiveness or inappropriateness of hydraulic protection. Their consequences, instead, depends previously on human activities.

During last decades, studies aimed at the mitigation of these adverse occurrences, shifted from a perspective of defending a territory from flood hazard, through structural measures that modify the characteristics of the flood event, to the approach of managing and reducing flood risk, through structural and non-structural measures that act on both flood hazard and its consequences.

An important effort in the passage from flood defence to flood risk management came from the 2007/60/EU Directive, which underlines the importance of "*prevention-oriented approaches, adopting early-warning systems, flood forecasting technics, land use regulation*". "*The purpose is to establish a framework for the assessment and management of flood risks, aiming at the reduction of the adverse consequences for human health, the environment, cultural heritage and economic activity associated with floods in the Community*" (European Council, 2007).

A challenge in flood risk management is certainly the need for the coordination of different stakeholders: city governments, national governments, ministries, public sector companies, including utilities, along with meteorological and planning institutions, civil society, non-government organizations, educational institutions and research centres, and the private sector. Policy makers require a clear vision of the alternatives and methods and tools to assist them in making choices. In addition, they should consider the large uncertainty associated with future predictions of flood patterns.

On the other side, technical specialists have to find techniques to study the feasibility, the costs and the advantages of different mitigation strategies under different scenarios. While the implementation and outcomes of flood risk mitigation measures can be defined in purely economic terms, technical specialists must also consider broader issues such as the impact of measures on environmental degradation, biodiversity, equity, social capital/capacity, and other potential trade-offs, always recognizing that the residual risk never reduces to zero.

The use of prevention measures that do not interfere on flood’s features requires the elaboration of methodologies and strategies aimed at verifying their effectiveness. All over the world, public governmental bodies and academics published some studies on the effectiveness of non-structural measures (Egli, 2002; Kreibich et al., 2005; Lasage et al., 2014), but the lack of data on it (or their coarseness) makes their reliability hard to know.

In fact, while it’s easy to calculate, for a fixed return period, how the construction of a levee or a dam make hazard change, it is not so easy to understand how the use of hazard-independent measures varies the attitude of a territory in suffering a negative event’s consequences. Considering the mathematical equation of Risk (Kron, 2005):

$$R = H\ V\ E$$

(where H is the hazard, V is the vulnerability, E is the entity (value) of the elements at risk), the variable describing this attitude is vulnerability, defined exactly as “the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard” (UNISDR 2009). Vulnerability embodies also the capacity of a system to anticipate, cope with and resist to flooding (resistance) and the capacity of the system to recover from the impact of flooding (resilience).

Because of its connection to elements’ susceptibility, vulnerability can be assessed as the expected loss degree of an element (or set element) at risk because of a hazardous event (Varnes, 1984; Fell, 1994). It then coincides with the relative damage associated to a certain event and can assume values ranging from 0 to 1, as the expected degree of loss varies from no damage to complete disruption.

In scientific literature there are many studies dedicated to the evaluation of flood hazard and over time many hydrological and hydraulic models able to describe the features of a given return period event have been developed. The existence of consistent databases of elements involved (measures of rainfall, discharge ...) has been a fundamental element of this goal and, today, we are able to derive the results and the uncertainties associated with them.

Conversely, studies addressed to the evaluation of flood damages are few and affected by uncertainties difficult to quantify. The main reasons which make damage estimation a challenging task are the numerous and hardly assessable variables on which it depends and the lack of consistent and reliable databases on flood damages.

In particular, damage is influenced by (Thieken et al., 2005; Merz et al., 2010, 2013): hydrodynamic factors, like flow velocity, flood frequency (Merz et al., 2009; Elmer et al., 2010) and duration; building characteristics, like its type and quality, the floor space or the number of flats; precautionary measures implemented at different scales (Egli 2002, Kreibich et al. 2005).

In general, flood damages are classified as a combination of direct, indirect, tangible and intangible. Direct losses are due to the direct contact of the element at risk with the flow; indirect losses include all consequences of the flood event that are not directly connected to the flow, like disruption of public services and commercial activities after the flood or outside the flooded area. In parallel, tangible losses can be specified in monetary terms, while intangible losses are not traded in a market and cannot be expresses in monetary terms.

Despite in some studies is underlined the consistency of indirect damages (EMA 2002), the majority of literature analysis focused on the assessment of direct tangible losses, while indirect losses are, often, roughly estimated and intangibles are frequently ignored or simply mentioned. The most widespread approach in direct tangible damage assessment foresees the adoption of damage functions, connecting damage to one or more variables (usually the only flood depth) influencing it.

Synthetic and empirical analyses are the two main approaches in developing damage functions. In synthetic approaches (ex-ante analysis) damages are estimated for standardized property types, while the proportional damage is estimated by expert judgement (e.g. the MultiColoured Manual method from Penning-Rowsell et al. 2005); empirical approaches, instead, use damage data derived from ex-post assessments of actual past events (e.g. the FLEMO damage model from Thieken et al. 2008). This second method requests the collection of a huge amount of ex-post damage information, but such datasets are still scarce.

Even if different damage assessment methods have been developed (HR Wallingford 2000, Sayers et al. 2002, Hall et al. 2003, Kok et al. 2004, Meyer and Messner 2005), the lack of high-quality basis data remains as the main obstacle to the derivation of uncertainties in ex-ante analysis. Even when data exist, their reliability is often compromised by: their scale, the value attributed to elements, the lack of common lines in damage collection during post-event surveys, their close dependence to the event from which they originate…

Following Italian regulations, the risk assessment in Sicily is carried out by means of the use of matrices that provide flood hazard and flood risk in function of the event return period, the inundation depths and the exposure classes of assets at risk (Regione Sicilia 2004). In this approach, the vulnerability has a constant value preventively equal to 1: this means hypothesize the complete disrupt of every element reached by the water.

This methodology substantially demonstrates how hazard varies in different zones more or less densely populated: in fact, the exposure classes give general information on buildings (economic and strategic) value and no information on vulnerability variations is included. It does not allow for quantitative assessment of risk (expected damage), which should be useful in flood risk management plans redaction or in cost-benefit analysis for the assessment of the effectiveness of protection strategies.

The idea of bypassing the assets' economical value and using exposure classes, actually, may reduce uncertainties in those cases when comprehensive databases are absent. Conversely, fixing the vulnerability default value equal to 1 inhibits any assessment of the variations in this parameter and, then, any possible comparison among different combinations of non-structural measures aimed at evaluating their effectiveness.

In this work, a new methodology for flood risk assessment, based on the definition of Exposure classes and the derivation of flood Vulnerability curves for buildings, is presented. The goal is to obtain an exposure-vulnerability crisscross classification. While both the building density and the strategic importance of the buildings influence Exposure, vulnerability is influenced by their constructive characteristics, by the implemented security measures or, vice versa, by the criticalities that make them suffer strong damages for few flood volumes. Vulnerability is therefore an intrinsic building feature: the same vulnerability curves may be used for sparse houses (low exposure) or buildings arising in town centre. That is why it is important not to neglect any of the two variables.

A 2-D hydraulic model was used to derive the hydrodynamic characteristic of the flood event studied. It integrates classical hydraulic equation by using a finite element technique with triangular elements. In order to minimize the error between the observation and the prediction data, the model has been calibrated with reference to floodplain and river channel roughness (assumed to be the most important parameter controlling the inundation extent). Once mapped (as output of the 2D model) the envelop of the maximum water depths inside the modelled area, the flooding depths inside the buildings have been derived on a GIS Platform, as the mean inundation depth value along their contours.

The starting point for Exposure classification came from the Sicilian Flood Risk Plan, that contemplates four classes, each one containing inhomogeneous elements with associated comparable strategical importance (e.g. small inhabited associated to primary roads and escapes, technological infrastructures with primary importance, cultural, architectural and archaeological asset under legal bond and industrial and craft settlements). Starting from this wide classification, each group was separated in subclasses containing each one elements with the same destination use. The second step consisted in the particularization of residential and public buildings in order to establish a scale among them, depending on their economic or strategic value.

Regarding vulnerability estimation, the idea in this work was to derive relative vulnerability functions for areas where both damage data and on site building inspections lack, so it was followed a synthetic approach.

To make the curves as generic as possible, instead of referring to building typologies with a specific geometry inside, it was considered the damage suffered by building's elements (floors, walls, doors, plants) and hypothesized the substitution cost of each element to derive its weight respect to the total substitution costs. To describe the proportional damage, we submitted a questionnaire to a team of experts, in particular a team of civil engineers working in Sicilian territory. The first results were relative damage curves associated to each element: by multiplying them for each one for its weight and by merging them, the global vulnerability curve for the studied element was obtained.

Different qualities of elements were accounted by considering buildings with associated poor, medium or rich finishes: for each class and considering two flood event durations (short and long, this last for events lasting more than 24 hours), different vulnerability curves for buildings were derived.

Vulnerability assessment has been implemented in a GIS environment by relating buildings-use and building internal inundation depth to the appropriate vulnerability curve.

The results of vulnerability analysis have been reported both in maps and in a Exposure-Vulnerability matrix, able to give us an idea of the actual situation of a catchment or to compare different scenarios. In each cell of the matrix, it can be seen which percentage of the total area is associated to each vulnerability class, distinguished for the different exposure classes.

The construction of a E-V matrix allows both to understand the actual situation of a catchment (and the possible consequences of a flood event) and to study the effectiveness of non-structural measures for a site, just studying how their implementation modifies the distribution of elements at risk inside it.

Chapter 1 – Generalities

1. Introduction

Many authors has studied flooding events' consequences among last decades. Jha et al. (2012) reported that in 2010 alone, 178 million people were affected by floods, while the total losses in exceptional years such as 1998 and 2010 exceeded $40 billion.

The Centre for Research on Epidemiology of Disasters (CRED) published, basing on its EM-DAT database and together with the UN Office for Disaster Risk Reduction (UNISDR), a report on the human costs of weather-related disasters occurred between 1995 and 2015. According to it, flooding alone accounted for 47% of all weather-related disasters, affecting 2.3 billion people (even if other type of disasters results to be more dangerous in terms of number of lives lost), the majority of whom (95%) live in Asia. "*In total, EM-DAT recorded an average of 335 weather-related disasters per year between 2005 and 2014, an increase of 14% from 1995-2004 and almost twice the level recorded during 1985-1994. The true economic cost of weather related disasters is also bleaker than EM-DAT data suggest (US$ 1,891 billion), since only 35% of records include information about economic losses; in Africa the figure is as low as 16.7%. Overall, annual economic losses from disasters are estimated by UNISDR at between US$ 250 billion and US$ 300 billion extrapolating from a study of nationally-reported disaster losses.*" The report is available on CRED website and other information are available in UNISDR (2015).

The European commission collected data on the costs of flood risk too. It estimated that, between 1998 and 2004, Europe suffered over

100 major floods (including the catastrophic floods along the rivers Danube and Elbe in 2002), which caused some 700 fatalities, the displacement of about half a million people and insured economic losses totalling at least € 25 billion (Commission of the European Communities, 2004, 2006).

Chatterton et al. (2008) reported that in the 2007 summer floods in the UK, of the £4bn damage to the economy, approximately £670m was credited to damages to critical infrastructure.

Flooding do not cause just economic losses, but it is responsible of a large percentage of all deaths from climate-related disasters. Ohl and Tapsell (2000) described flooding as predominate cause of death associated with natural disasters in the United States and reported that *"flooding accounts for 40% of all natural disasters worldwide and causes about half of all deaths from natural disasters. Most floods occur in developing regions and tropical regions where the impact on public health is substantial, the number of people displaced is often large, and the number of deaths is high"*.

This last consideration is sadly worsen by the data provided by UNESCO (2004), according to which *"one billion people, the majority of whom figure among the world's poorest inhabitants, are thought to live in the potential path of a 100-year flood. Floods are the most destructive type of water-related disaster. Between 1991 and 2000, more than 665 000 people died in 2557 natural disasters, 90% of which were water-related. From 1971 to 1995, floods affected more than 1.5 billion people. More than 81 million were left homeless. Asia is most at risk, some 228 000 people having perished between 1987 and 1997 in floods that caused economic losses of $136 billion"*.

During last decades, studies aimed at the mitigation of these adverse occurrences, shifted from a perspective of defending a territory from flood hazard, through structural measures that modify the characteristics of the flood event, to the approach of managing and reducing flood risk, through structural and non-structural measures that act on both flood hazard and its consequences.

This shift request the deepening of topics related to the estimation of flood consequences (e.g. vulnerability assessment, integrated approaches for risk reduction and analyses of measures' feasibility…). Considering risk as the product of flood hazard, territory exposure and vulnerability (Kron, 2005), this last variable describe the attitude of a territory to suffer the negative expected loss degree and, consequently, can be assessed as the relative damage associated to the flood.

In scientific literature there are many studies dedicated to the evaluation of flood hazard and over time have been developed many hydrological and hydraulic models able to describe the features of a given return period event. The existence of consistent databases of elements involved (measures of rainfall, discharge ...) has been a fundamental element of this goal and, today, we are able to derive the results and the uncertainties associated with them.

Conversely, studies addressed to the evaluation of flood vulnerability are few and affected by uncertainties difficult to quantify. The main reasons which make vulnerability estimation a challenging task are the numerous and hardly assessable variables on which it depends and the lack of consistent and reliable databases on flood damages.

In this chapter, a general overview on flood risk management approach, risk variables and inherent European and local regulations is given. Section 4, then, is entirely dedicated to an overview on flood damage assessment.

2. Floods: from defence to flood risk management

The destructive consequences of floods are increasing in many parts of the world, not only due to changes in climate, but also largely due to continuous population growth along floodplains and to changes in land use. (Milly et al., 2002; Di Baldassarre et al., 2010; Jha et al., 2012). The population growth shows as its defining feature the urban settlements' expansion. As reported in Jha et al. (2012), in 2008, for the first time in human history, half of the world's population lived in urban areas, with two-thirds of this in low-income and middle-income nations. This is estimated to rise to 60 percent in 2030, and 70 percent in 2050 to a total of 6.2 billion, or double the projected rural population for that time.

With the increase in urban population, urban floods become a focus point in global flood impact. This aspect becomes more evident if we think that this fast growth makes urban settlements grow in the form of unplanned development in floodplains, in coastal and inland areas alike, as well as in other flood-prone areas.

Urban areas can be flooded by rivers, coastal floods, pluvial and ground water floods, and artificial system failures. Usually floods are the result of meteorological and hydrological extremes combined with ineffectiveness or inappropriateness of hydraulic protection. Their consequences, instead, depends previously on human activities.

2.1 Flood defence and structural measures

The classic approach of flood defence foresaw the implementation of structural protection measures aimed at reducing flood event severity in flood prone areas. Heintz et al. (2012) defined this approach, in which social aspects leading to an increase of potential damage are not considered, as *security approach*.

The “structural” protection measures interfere directly with the flow, modifying the flooded area extension and the hydrodynamic features of the flow. They are also called *flood control strategies*, because they aim at reducing the flood hazard, i.e. the probability of flooding.

Structural measures range from hard-engineered structures such as flood defences and drainage channels to more natural and sustainable complementary or alternative measures such as wetlands and natural buffers.

These solutions are generally oriented at a standardized level of protection (usually the 100-year flood), creating so a line of demarcation between areas at risk and “safe” areas and neglecting the residual risk associated to protections failure for extreme flood events.

This residual risk can be more dangerous than the one associated to the absence of protections, for two reasons.

The first is because the failure of structural measures (e.g. dikes) for extreme events worsens the hydrodynamic features of the flow, as it hit the territory with incremented velocities and, consequently, stresses.

The second depends on the lack of communication about the residual risk (Buchecker et al., 2013). The practice of raising the heights of river levees or dikes, for instance, makes inhabitants perceive that all flood risk have been eliminated (Burton and Cutter, 2008). Citizens and businesses in “protected” areas are so unaware of being at risk and accumulate remarkable amounts of values, such incrementing the exposure in the area: this result in an increase of potential damage (Vis et al., 2003). Given that risk can be defined as a combination of the probability of flooding and its potential adverse consequences (Helm, 1996), in fact, raising the levee systems reduces the flooding probability, but the potential adverse consequences (flood damage) might significantly increase. This occurrence is defined as *safe development paradox* (Burby, 2006) or *levee effect* (Burton, 1962; Segoe, 1937).

The security approach, focused on flood hazard control and reduction, has therefore a partial influence on floor risk. Flood hazard, in fact, representing just a component of flood risk, need to be combined with the consequences that the eventual hazardous event may cause to answer the question on which risk can be associated to a territory.

2.2 Flood risk management and integrated approaches

Flood risk management can be defined as the “*continuous and holistic societal analysis, assessment and mitigation of flood risk*” (Schanze, 2006).

Or as “*a process of continuous analysis, adjustment and adaptation of a flooding system (including both structural and non-structural actions) taken to reduce flood risk*” (FLOODsite, 2009a; HR Wallingford, 2007).

The concept of risk implies a transition from the classical approach of defending a territory from flood hazard, through structural measures that modify the characteristics of the flood event, to the approach of reducing flood risk, through structural and non-structural measures that act on both flood hazard and its consequences. This include a shift away from the single objective of flood defence towards management of flood risks proper through also influencing the vulnerability of society. The IRMA-SPONGE research programme emphasized this aspect in one of its four main conclusions: "The most effective flood risk management strategy is damage limitation by spatial planning and land use adaptations" (Hooijer et al., 2004).

Merz et al. (2010a), following other studies (Hall et al., 2003; Sayers et al., 2002), described this shift in a very condensed form by three developments:

- managing all flood events focusing on the idea of coping with risk, instead of defining a design flood event from which implement protections;
- risk-informed decision making, so that risk estimates may be used to inform multiple decision makers and the amount invested in risk reduction could be in proportion to risk magnitude and to the cost-effectiveness with which that risk may be reduced;
- integrated system approaches, complementing or replacing flood defence by (non-structural) measures for reducing effects of flooding.

Non-structural measures, in fact, intend to keep people safe from flooding through better planning and management of urban development, thus acting on flood consequences rather than flood hazard. They incorporate a wide range of solutions, such as warning systems, emergency measures, spatial planning regulation, flood-proofing of buildings or insurance solutions, which contemplate the possibility of coping with hazard, rather than trying to reduce it to zero.

The same event can led to deeply different consequences if it occurs in urbanized area rather than in inhabited ones. This aspect underlines how risk is a concept in continuous evolution and that no structural measure will never completely cancel risk: even when hazard is strongly reduced, the presence of elements at risk in flood prone areas itself makes risk positive.

Including the possible consequences in flood risk management adds to its implementation all the many variables influencing these consequences, making flood risk management a complex, multi-variate problem facing many uncertainty sources.

Heintz et al. (2012), giving an overview on the implementation of the floods directive in Germany, described the differences between flood protection and flood risk management approach and reported a table by Wagner (2008) with a synthesis of the comparison (here in Table 1).

Table 1. Comparison of security approach and risk approach (Heintz et al., 2012; Wagner, 2008).

Main characteristics	Security approach	Risk approach
Aim	protection against threat emanating from flood events	develop a strategy how to handle flood risk, define which level of risk is acceptable
Terminology	danger, threat, security, protection	risk, residual risk, risk evaluation, risk management, risk governance
Scenarios	medium-probability events as the standard level of protection	high-/medium- and low-probability events, priorities regarding level of protection
Measures	focus on structural measures	combination of structural and non-structural measures
Involved parties	sectorial planning (water authority), top-down, implementation gap	interdisciplinary, bottom-up elements
Spatial focus	local solutions for local problems, oriented at administrative borders	across administrative borders, catchment-based
Time aspect	short-term solutions, event-driven, “trial and error”	medium-/long-term solutions, prevention, regular revisions

A challenge in flood risk management is certainly the need for the coordination of different stakeholders: city governments, national governments, ministries, public sector companies, including utilities, along with meteorological and planning institutions, civil society, non-government organizations, educational institutions and research centres, and the private sector. Policy makers require a clear vision of the alternatives and methods and tools to assist them in making choices. In addition, they should consider the large uncertainty associated with future predictions of flood patterns.

On the other side, technical specialists have to find techniques to study the feasibility, the costs and the advantages of different mitigation strategies under different scenarios. While the implementation and outcomes of flood risk mitigation measures can be defined in purely economic terms, technical specialists must also consider broader issues such as the impact of measures on environmental degradation, biodiversity, equity, social capital/capacity, and other potential trade-offs, always recognizing that the residual risk never reduces to zero.

Jha et al. (2012) indicated twelve key principles for integrated urban flood risk management, as a synthesis of a wide overview on the basis for flood risk management policies implementation.

2.3 Flood risk management in the EU

Under the European Flood Action Programme (EC, 2004), the European Commission combined activities to enhance knowledge and methodological skills for the scientific-based risk management on the one hand and to prepare a legal instrument for a common approach of societal flood risk management in the Member States on the other hand. The latter led to the implementation of the European Directive 2007/60/EC on the assessment and management of flood risks (Floods Directive) which entered into force on 26 November 2007.

The 2007/60/EU Directive underlines the importance of "*prevention-oriented approaches, adopting early-warning systems, flood forecasting technics, land use regulation*". "*The purpose is to establish a framework for the assessment and management of flood risks, aiming at the reduction of the adverse consequences for human health, the* *environment, cultural heritage and economic activity associated with floods in the Community*" (European Council, 2007).

Klijn et al. (2008) studied the approaches of different European countries (England and Wales, France, Germany, Hungary, Italy and the Netherlands) facing the new Directive. They found that the move from flood protection and defence to comprehensive flood risk management was already reflected in many national policy frameworks, but policies in different countries were at an initial stage and no common lines were identified. In general, they found out common ingredients of flood risk management process: *1) appropriate governance and institutional arrangements, 2) implementation of physical (structural) and non-structural measures, and 3) maintaining and optimising the performance of these measures*.

Another result of the 2004 European Flood Action Programme has been the identification of the Sixth Framework Programme Integrated Project (IP) FLOODsite as contributing to the improvement of integrated flood risk analysis and management methodologies. The five-year (2004-2009) project was the largest European Commission project on floods, contemplating 35 Tasks and involving a team of over 200 researchers from 37 institutions in 13 countries (FLOODsite, 2009b). The project *was funded to study the issue of flooding and associated risks and to develop and test innovative approaches to support flood risk management under real-world conditions* (FLOODsite, 2009c). It significantly influenced the way of thinking and scientific approaches in the field of comprehensive flood risk management (Klijn and Schweckendiek 2013). Examples, tools and techniques supporting Integrated Flood Risk Management provided by the project can be accessed from FLOODsite website.

A section about the risk-based approaches that integrate risk evaluation and management is beyond the scope of this general overview. Here are reported just few general information on the matter (Meyer et al., 2013).

The traditional approach for an economic assessment of mitigation strategies, in order to find the most efficient solution, is Cost-Benefit

Analysis (see e.g. MAFF, 1999). It still has two main limits: cost assessment is still far from delivering precise monetary figures for costs associated to natural hazards; Cost-Benefit Analysis would however be embedded in a wider Multi-criteria Analysis to allow decision makers to decide on different solutions, given their related uncertainties (Green et al., 2011). An alternative is the Cost-Effectiveness Analysis, in which the advantages of the mitigation strategies are expressed in non-monetary terms, choosing a common target indicator (Meyer et al., 2012).

3. The variables of risk equation

The passage from hazard to risk is represented in FLOODsite (2009a) through the Source-Pathway-Receptor model (ICE 2001, Fleming 2002, in Figure 1a) adding as final synthesis flood consequences (Figure 1b): the steps leading flood to its consequences are so synthetized. Hazard, in fact, is a necessary input for risk but does not necessary cause harmful outcomes: harms depend on the exposure to the hazard and the characteristics of the receptors (on which we have the greatest control). In a similar way, a disaster can only occur when people are harmed and/or their belongings damaged.

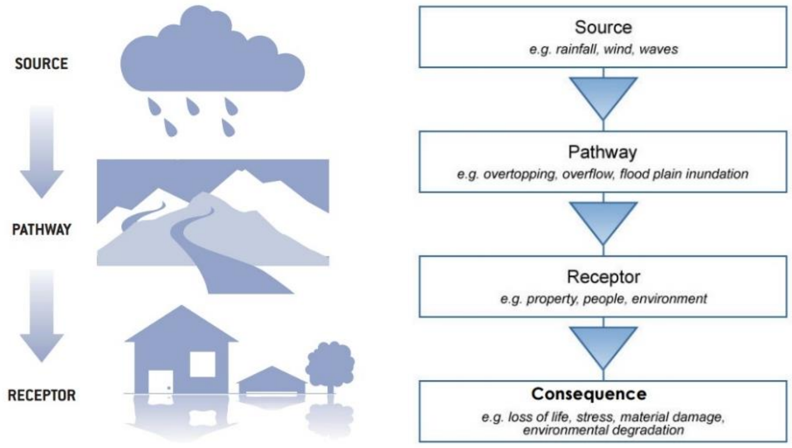

Figure 1. a) Source-Pathway-Receptor model (ICE, 2001; Fleming, 2002); b) Source-Pathway-Receptor-Consequence model (FLOODsite 2009)

Risk can so be defined as a function of probability of flooding and flooding consequences, these last functions of exposure characteristics and vulnerability of the exposed socio-economic system. As pointed out in Klijn et al. (2008), risk definitions *do urge one to consider the fact that (i) without people or property there is no risk, and (ii) that one should pay equal attention to the flood hazard and a society's vulnerability*.

The mathematical equation of risk, introduced by Kron (2005) to study the probable maximum losses resulting from an extreme event, can be written as:

$$R = H \cdot V \cdot E \qquad (1)$$

Where:

H is the hazard: the threatening natural event including its probability of occurrence;

V is the vulnerability: the susceptibility of a system to the negative effects of a hazard;

E is the ensemble of the elements at risk.

In following sections a general deepening of each one of this variables.

3.1 Hazard

Over the past decades, an increase in occurrence frequency and magnitude of high flows has been registered. Urbanization in flood prone areas contributed largely in developing this trend on different levels.

New settlements areas lead to a reduction in the storage volumes of natural retention areas and, on the other side, to the straightening of river channels to make room to the new constructions and to the raising of dikes to prevent agricultural areas from being flooded. These aspects cause an increase in flood hazard downstream, as flow velocities and peak discharges rise.

Another example of anthropogenic influence is the increase of impermeable or at least less permeable surfaces such as houses, roads, parking lots, etc. which cause a further increase in the runoff and – in some cases – in the peak flows of the rivers.

A huge amount of examples of circumstances modifying flood hazard exists, but what we are interested in is how hazard can be estimated and its role in flood risk assessment.

Hazard describes the spatial extents of overall adverse effects caused by flooding for a particular area. It depends on several parameters, such as flood depths, flow velocity, duration of flooding, product of water depth by flow velocity, rate of water rise, concentration of sediments or other transported materials, pollution load of water… One or more of them can describe hazard, depending on the study area and the flood characteristics (see e.g. examples in Kelman and Spence, 2004, or Tingsanchali and Karim, 2005).

Despite the several parameters influencing hazard, it is commonly described by the only flood depths and flow velocities. There are in fact several water depth-velocity hazard curves in scientific literature, for different elements at risk, like houses, vehicles, persons, etc. (see e.g. ACER Technical Memorandum No. 11, 1988; Penning-Rowsell and Fordham, 1994; Marco, 1994; Stephenson, 2002).

Another element playing an important role is the return period: higher hazard index could be associated with floods occurring frequently, while the hazard related to low probability (e.g. if the expected number of floods in 300 years is 1) may be tolerable. The common unit is the year: hazard is then expressed as function of the annual probability of occurrence of a damaging phenomenon with associated fixed hydrodynamic features.

The Italian Flood Directive refers to four hazard classes, expressed for three different return periods and related to flood depth and flow velocity: the boundaries of each class depends on considerations on human stability.

Ideally, every hazard classification should be periodically revised because of the floodplain development or of the availability of better topographic data, models, or statistical data.

3.2 Vulnerability

Many scientific disciplines work with vulnerability: natural scientists, engineers, social scientists or economists, to name just a few. The term "vulnerability" has then different interpretations, as exist different epistemological positions of research traditions and because of differing objectives of research in these areas (Birkmann, 2006; Füssel, 2007; Hufschmidt, 2011).

The Intergovernmental Panel on Climate Change IPCC defines vulnerability within its third assessment report (McCarthy et al., 2001) as *"the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity"*.

The United Nations Office for Disaster Risk Reduction (UNISDR) defines vulnerability as "*the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard*" (UNISDR 2009).

Fuchs et al. (2007) reported in a table a compilation of different definitions of the term vulnerability with respect to natural hazards research (extended from information in Cutter 1996 and Weichselgartner 2001). From a natural science perspective, studies on vulnerability focus on the susceptibility of physical systems in areas at risk to natural processes, with the aim of providing information useful in risk mitigation strategies.

Vulnerability embodies also the capacity of a system to anticipate, cope with and resist flooding (resistance) and the capacity of the system to recover from the impact of flooding (resilience).

In the practical application, vulnerability is often related to exposure, defined as the maximum number of lives being present in endangered areas (e.g., Schuster and Fleming, 1986; Keiler et al., 2005). Actually, the relation between these two variables is still source of misunderstanding. In particular, some authors (such as Braun and Aßheuer, 2011, Scheuer et al., 2011 and Willroth et al., 2012) consider exposure as a component of system vulnerability, instead of sharply separate these two variables.

During last decades, the definition of a common line in this sense was impossible, due to the different purposes of the conducted studies. The best solution, suggested by Fuchs et al. (2007) is *"to clearly describe and define which components of risk and/or vulnerability assessment are considered in each individual study. These components may include (1) the frequency and magnitude of a hazard, (2) elements at risk and their exposure to this hazard, (3) the susceptibility of these elements at risk to the hazard and (4) the coping and adaptation capacities of various categories of elements at risk"*.

The interpretation assumed in this work is now reported. Vulnerability is clearly related to the consequences of a natural hazard, which are generally measured in terms of damage or losses. Likewise, given its general connection to elements' susceptibility, it can be assessed as the expected loss degree of an element (or set element) at risk as a consequence of a hazardous event (Varnes, 1984; Fell, 1994).

Consequently, vulnerability can assume values ranging from 0 to 1, as the expected degree of loss varies from no damage to complete disruption. Its assessment involves in many cases the evaluation of several different parameters and factors, connected both to the flood characteristics, and to the intrinsic features of elements at risk. These parameters are impossible to be measured, but they are assessable only by means of the use of indices or variables. They are, e.g., building materials and techniques, state of maintenance, presence of protection structures, presence of warning systems and so on (Fell, 1994; Fell and Hartford, 1997).

Section 5 of this chapter is entirely dedicated to a deepening on flood damages features and assessment methodologies. Indeed, one of the focus of this work has been the derivation of curves for the estimation of flood vulnerability and, because of its assessment as expected loss degree of an element, it coincides with its relative flood damage.

3.3 Exposure

Exposure evaluations are needed to identify and list assets in areas at risk. Exposed objects can be grouped basing on common functions and/or attributes.

Land use map represent an exposure classification, as it is possible to associate to their classes specific information on densities and typologies of elements at risk. An example of land cover map containing consistent localized geographical information is the Corine Land Cover map. Based on interpretation of satellite images, it is a map of the European natural and artificial landscape and provide information on the land use of the Member States of the European Community.

Information can be derived, as well as from land use maps, even from field surveys or official statistics at different spatial scales. What is important is their upscaling or downscaling in order to make them compatible with hazard and vulnerability data.

In damage to buildings assessment according to the HAZUS-MH Flood Model (FEMA, 2003; Scawthorn et al., 2006), for example, uniform attributes are assigned to each occupancy class in a given census block. On the other side, flooding depths are weighted throughout the census block and default damage functions at the same scale are used to derive relative damage and then multiplied for depreciated values assigned to each occupancy class.

When adopting absolute damage curves (see section 5.5), the exposure analysis contemplate only the identification and classification of exposed objects: exposure is so described in terms of affected sectors, without contemplating monetary values. When adopting relative damage curves, instead, the results in terms of relative loss have to be multiplied for assets values in order to obtain a quantitative assessment of risk consequences. These values vary in time, following economic trends, and in space, because the same object can have different values in different regions. The variation in time request a periodical update of estimations; the variation in space could request the use of local data for the analysis.

Figure 2 shows a scheme to better understand the different path leading to flood risk assessment whether or not exposure is assumed as included in vulnerability. To distinguish the variables, Exposure is considered as the pure identification of assets at risk and expresses the nominal value attributed to the same elements in function of their strategic, economic and functional role. On the other side, the monetary values of assets is identified with the variable Entity that, together with vulnerability, determines their corresponding absolute damage functions.

Assuming the flooding depths as the unique parameter describing Hazard and influencing Vulnerability, the corresponding damage functions are simple curves. When associated to elements Entity, they are absolute damage curves: carrying out different damage analyses for different flooding frequencies (expressed through events' return period) allow the derivation of flood risk as absolute damage attended. When, instead, Exposure represents the only data available on assets at risk, the vulnerability assessment conduces to a crisscross assessment of flood consequences (for a given event): again, this analysis repeated for different returning period may led to the same crisscross evaluation of the attended consequences (for events associated to different probabilities of occurrence).

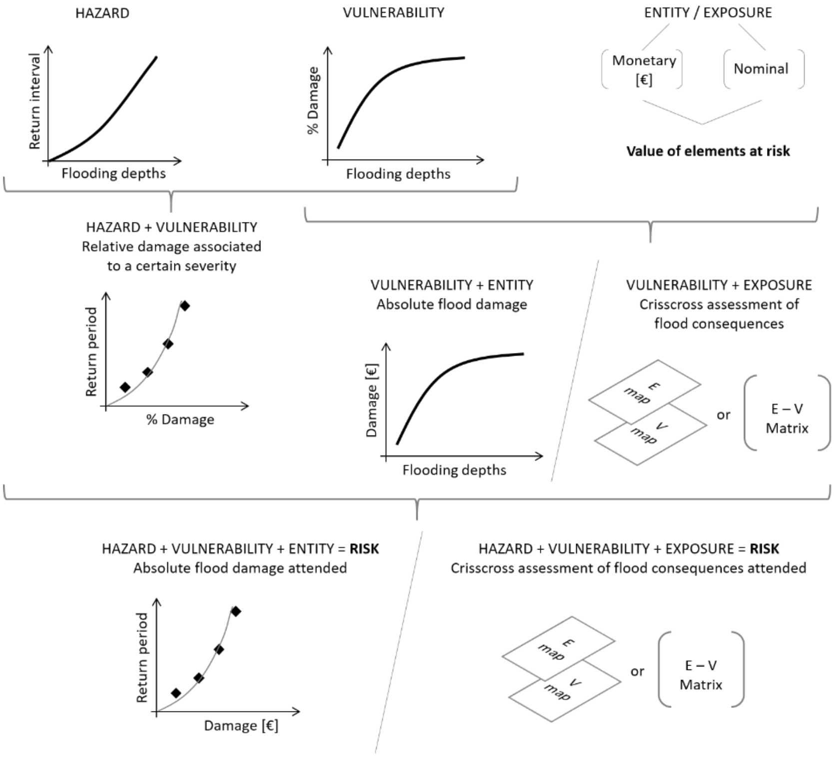

Figure 2. Overview on the interactions among risk variables.

In Merz et al. (2010) an overview on different methodologies and approaches for the estimation of exposure data, including examples and discussions on different disaggregation methods used to downscale or improve coarse data.

4. The EU Flood Directive and the Italian regulations

4.1 *EU Directives*

At European level, the reference regulations for water protection and flood risk assessment and management are the 2000/60/EC Directive and the 2007/60/EC one.

The first one, among others, stipulates the obligation for the Member States to:

- *identify the individual river basins lying within their national territory and, for the purposes of this Directive, shall assign them to individual river basin districts;*
- *identify of the appropriate competent authority, for the application of the rules of this Directive within each river basin district lying within their territory*;
- *produce a river basin management plan for each river basin district*.

The 2007/60/EC Directive, instead, has the purpose *to establish a framework for the assessment and management of flood risks, aiming at the reduction of the adverse consequences for human health, the environment, cultural heritage and economic activity associated with floods in the Community.*

The proposition for the preparation of a European Directive for floods management was first mentioned in the Floods Action Programme prepared by the European Commission. Its first draft was released in January 2006 after a public consultation (Commission of the European Communities, 2006). The negotiations of the Member States concluded unanimously in the final text of the Directive on 27 June 2006, that was later adopted as Common Position of the Council on 18 October 2006. Directive 2007/60, then, entered into force in November 2007.

The new directive implementation is based on three consecutive steps: the preliminary delineation of flood-prone areas; the predisposition of flood hazard maps and flood risk maps resulting for the foreseen probability scenarios (flood scenarios are formulated corresponding to high, medium and low probability); the establishment of flood management plans.

While the flood hazard maps show the highest inundation water depths in the entire domain, the flood risk maps show the corresponding damage/losses at each cell of the computational field. From the above two maps, improvement measures can be evaluated basing on a clearly rational approach.

Tsakiris (2014), presenting a systemic paradigm for the assessment of flood hazard and flood risk in the riverine flood-prone areas, underlined the difficulties in the application of this Directive. These are mainly due to the data required and to the lack of practical indications on how to pass from flood hazard to flood risk maps and from risk maps to risk management plans. Detailed data, especially on assets and economic activities, are rarely available and space and time varying. The passage from hazard to risk, corresponding to the passage from severity to damage, require much more information in respect to the highest inundation water depths for three probability scenarios reported in flood hazard maps (section 5 of this chapter is totally dedicated to this topic). Regarding the request to establish plans addressing all aspects of flood risk management, it necessarily implies the elaboration of risk maps assessing expected damages/losses for each probability scenarios and foresees the analysis of a wide group of measures to establish their effectiveness and their prioritisation in order to reduce residual risk. As the previous and inevitable step, this is still a challenging task in many countries.

4.2 *Italian regulations*

The EU flood Directive was transposed in Italy through the legislative decree number 49, issued on 23 February 2010.

Already in 1989, however, two laws for soil conservation foresaw by the Basin Authorities the drafting of Basins' Plan, as cognitive, operative and technical tool for the planning of rules for soil conservation and water use regulation.

Later, in 1998, a new law introduced the concept of risk, giving the directions for the drafting of Plans aimed at the reduction of flood risk. The Plans had to contain the identification of areas at risk, joining information on susceptibility to flooding (for low, medium and high probability of occurrence) and settlements and human activities perimeter. In addition, the identification of measures for the protection of areas at risk had to be carried out. The same law, adopted in Sicily, led to the draft of a Flood Management Plan in 2004.

In Sicily the risk assessment still refers to the 2004 Flood Risk Plan. It is so carried out by means of the use of matrices which provide flood hazard and flood risk in function of the event return period, the inundation depths and the exposure classes of assets at risk (Regione Sicilia 2004). A first matrix is used to derive the hazard (the Plan refers to 4 hazard classes), in function of the water depth (as unique characteristic describing flood intensity) and of three different return periods (50, 100 and 300 years). Then, a second matrix provides the risk class in function of the class of hazard previously derived and the Exposure class. While using the second matrix, the Vulnerability is implicitly considered equal to 1, which means hypothesize the complete disruption of every element reached by the water.

The Exposure varies from E1 to E4, depending on both the density and the social/economic importance of elements at risk (in the class E1 are grouped cemeteries, sparse houses, farming settlements, etc., in the class E4 are grouped towns and significant public buildings like hospitals schools, etc.).

Even the Risk variable is described through four classes, varying from low to very high risk: the first class refers to areas that may suffer moderate damages from the design event; the last to those areas that may suffer a complete disruption with possible casualties.

This methodology substantially gives as result how hazard varies in different zones more or less densely populated: in fact, the exposure classes give a general information on buildings (economic and strategic) value and no information on vulnerability variations is included. It does not allow for quantitative assessment of risk (expected damage), which should be useful in flood risk management plans redaction or in cost-benefit analysis for the assessment of the effectiveness of protection strategies.

The idea of bypassing the assets' economical value and using exposure classes, actually, may allow to reduce uncertainties in those cases in which strong databases supporting the analysis lack. Conversely, fixing the vulnerability default value equal to 1 inhibit any assessment of the variations in this parameter and, than, any possible comparison among different combinations of non-structural measures aimed at evaluating their effectiveness.

5. Flood damages

Damage assessment of natural hazards supplies crucial information to decision support and policy development in the fields of natural hazard management and adaptation planning to climate change. As flood risk management is becoming the dominant approach of flood control policies throughout Europe, the estimation of economic flood damage is gaining greater importance, but it still represents a challenge. Following sections give a general overview on the typologies and the assessment methodologies of flood damages.

5.1 Flood damage typologies

The term damage embodies a wide range of meanings and interpretation, as it has been and is used by different experts facing different problems, each one dealing with his own discipline (economy, law, medicine, geography, etc.).

Generally speaking, it is possible to find some common lines in these multiple interpretations. Damage is always the consequence of an action or an event; it may affect material or immaterial goods; the preventive assessment of possible damage is the starting point in every risk management strategy.

From the flood risk management point of view, the best way to interpret the role of damages is to start from the definition of risk. Risk is defined (as introduced in previous sections) as *the combination of the probability of an event and its negative consequences* (UNISDR) or, in other words, risk represents the expected damages associated to flood event of different probability of occurrence (and, consequently, different intensities). What must be investigated, so, are the whole effects of a flood on a territory, which cover a wide range of “impacts”: impacts on humans, their health and their belongings, impacts on public infrastructures, cultural heritage and ecological systems as well as impacts on industrial production and the competitive strength of the affected economy (FLOODsite, 2007).

To make order in this wide ensemble of impacts, a classification among them has been researched and studied to define common distinctions worldwide. The two main criteria to distinguish among flood damages are the distinction between direct and indirect impacts, as well as the distinction between tangible and intangible ones.

Direct losses are due to the direct contact of the flow with the element at risk, including for example buildings and infrastructure disruptions: they results from the physical disruption of these elements.

Indirect losses, instead, include all consequences of this physical disruption, but they are not directly connected to the flow. These indirect damages may happen at different spatial and/or temporal scales in respect to the flood: they include disruption of public services and commercial activities after the flood or outside the flooded area, emergency and recovery costs, etc. The temporal shift can be due to the time needed to recover from the emergency and to restore the public services and the commercial activities interrupted (when this is possible). The spatial shift can be due to the repercussion that a commercial activity failure has on the other forward-linked (rely on regional markets for their output) or backward-linked (rely on regional sources of supply) activities (Cochrane (1997)). Some authors (e.g. van der Veen, 2003), while maintaining this classification, distinguishes inside the indirect losses: the business interruption costs that relate specifically to flooded businesses as primary indirect losses; the multipliers in the economy as secondary indirect losses.

Referring to the second criteria to distinguish damages in function of their estimation, tangible losses can be specified in monetary terms, while intangible losses are not traded in a market and cannot be expresses in monetary terms (injures, damages to cultural heritage buildings …). Molinari (2011, 2013) listed in a table damages, classifying them both considering their nature (of direct, indirect, tangible, intangible) and according to the exposed element (residential, commercial or public buildings, people, infrastructures, cultural heritage…).

Despite in some studies is underlined the consistency of intangible damages (EMA 2002), the majority of literature analysis is aimed to the assessment of tangible losses and, in particular, to direct tangible ones. In fact, direct damages are usually present in any damage assessment, indirect losses are often roughly estimated and intangibles are frequently ignored or simply mentioned.

While it is easy to imagine, because of their definition, the difficulties in evaluating intangible losses, even flood tangible damages assessment is still a research challenge: the main obstacles in these research fields are the lack of available and consistent database and the many variables involved in the problem.

5.2 Influencing variables in flood damage assessment

In section 3.2, when introducing flood vulnerability, it has been explained why it coincides with the percentage of damage that assets in areas at risk may suffer. It depends not only on flood features, but also on the intrinsic characteristics of the affected element. In particular, this damage is influenced by (Thieken et al. 2005, Merz et al. 2010, Merz et al. 2013):

- hydrodynamic factors, like flow velocity, flood frequency (Merz et al, 2009; Elmer et al., 2010) and duration, contamination indicator;
- building characteristics, like its type and quality, the floor space or the number of flats;
- precautionary measures implemented at different scales, like early warning and emergency measures, preparedness, private precautionary measures (ICPR 2002, Kreibich et al. 2005).

Thieken et al. (2005), stating from the concept that the damage of a building is dependent upon the load on the structure on the one hand and its resistance on the other hand, classified the influencing factors in impact and resisting ones (Figure 3) and studied their influence on flood damages to private households. Thanks to a survey among flood-affected private households (Kreibich et al. 2005a, Thieken et al. 2007) undertaken in Germany in the aftermath of the 2002 flood, they found that impact variables weight more than resistance ones, but an important effort to classical damage studies would come by accounting more variables in respect to the only water depth (e.g. contamination).

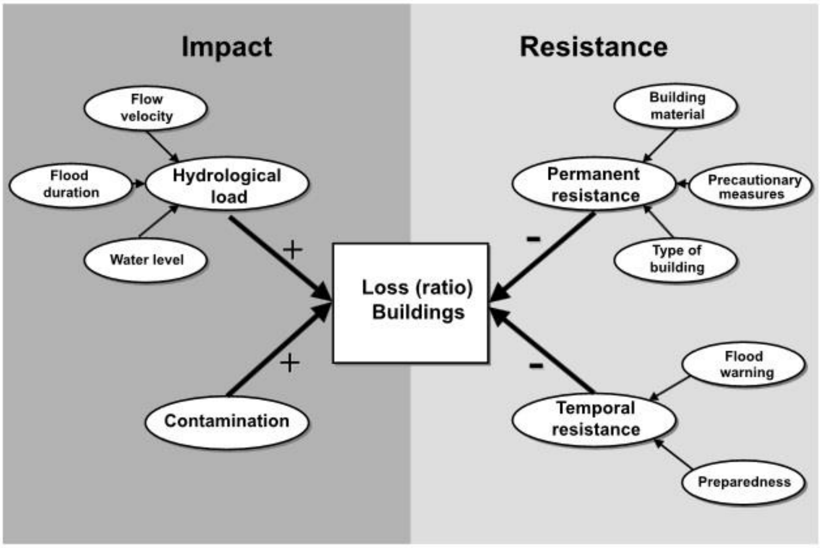

Figure 3. Factors influencing the flood loss (ratio) of buildings (Thieken et al., 2005)

Merz et al. (2013) studied the importance of influencing variables using regression trees and bagging decision trees, in order to consider the interactions among them. They found out that, in accordance with previous flood damage analysis, water depth is the most important predictor. Contamination and flow velocity influence, indeed, is particularly important only for water depths smaller than 97.5 cm, thus confirming a previous study by Kreibich et al. (2009) on the influence of water velocity on damage. Another variable they investigated is floor space of buildings and they found that it is important only for water depth higher than 97.5 cm and that the larger the building (and the higher its value) the lower its loss ratio. Thieken et al. (2005) gave, in particular, a limit value of floor space of 120 m^2, over which the loss ratio decreases.

Given the growing importance that international community is giving to non-structural measures in flood risk management, a group of influencing variables whose impact has been recently studied is the ensemble of precautionary measures, implemented at different scales. The report "Non Structural Flood Plain Management – Measures and their Effectiveness" by the International Commission for the Protection of the Rhine (ICPR, 2002) evaluates the effectiveness of various measures, depending on their capability to reduce or increase the existent damage potential, considering floods of different frequency and intensity. The damage reduction is given in absolute monetary values and in percentage classes but, unfortunately, it remains unclear on which data basis these estimates rely on.

Kreibich et al. (2005a), again basing on the 2002 flood in Germany, studied the effectiveness of protection measures implemented in residential buildings. This implementation, as expected, is connected to households awareness and, consequently, to their past experiences: measures of precaution are so mainly effective in areas with frequent, small floods (IPCR 2002). But Kreibich et al. (2005a) found that, even during the extreme flood event in 2002, many precautionary building measures significantly reduced the flood loss. Private water barriers and flood adaptation building structure as stable building foundation or waterproof sealed cellar walls reduced slightly loss ratio (24-29%), as they did not influenced contents damage: a larger reduction should came from cellar absence. Vice versa, flood adapted use, adapted interior fitting as well as the installation of heating and electrical utilities in higher storeys reduced the mean damage ratios of buildings by 46%, 53% and 36%, respectively. Another result is that after the flood, one or more building precautionary measures were undertaken by 42% of the households.

The results relative to flood adapted use and interior fitting have been confirmed by Merz et al. (2013), as they found that these variables reduce flood losses, but only for water depths smaller than 97.5 cm: this indirectly confirms also the IPCR (2002) assertion that private precaution is most effective in areas with low flood water levels.

As already said, most of the presented damage influencing factors are neglected in damage modelling, since they are difficult to predict, very heterogeneous in space and time and there is a very limited information on their effect. Merz et al. (2010), extending previous works (Gissing and Blong, 2004; Kelman and Spence, 2004; Merz, 2006; Forster et al., 2008), listed the studies on the influence of different factors, synthetizing such information in a table.

5.3 Spatial and temporal scales

The damage analysis can be carried out at different spatial and temporal scales. This information is important and becomes central when comparing different methodologies and applying them to different contests in respect to the one they are developed for.

About the spatial scales, the data can be referred to:

- micro-scale, when single elements at risk (buildings, commercial activities, infrastructures, …) are considered and damages refer to each of them;
- meso-scale, when elements at risk are aggregated giving as result land-use units (e.g. residential areas, public use, …) or administrative units (e.g. districts, zip code areas, …);
- macro-scale, when large spatial units (e.g. municipalities, or even regions or countries) are the base for damage assessment.

Methodologies (e.g. damage functions) developed for a specific spatial scale need upscaling and downscaling procedures to be adapted to other scales' analyses. The same attention must be paid when using databases: the data collected have always a spatial scale and the instruments derived follow the same scale: e.g. when collecting damages at the micro-scale for the empirical derivation of damage functions, these functions must be applied at single units to derive their damages for specific events.

A particular caution is needed when transferring data or methods available at meso-scale or large-scale analysis: the transferability, in fact, is limited by the chosen aggregation. The same aggregation must be chosen for the different location to be analysed or upscaling and downscaling procedures ad hoc are needed.

Another consideration needed when choosing the scale of analysis, is that when a hazardous event hits a territory causing interruptions in commercial activities, surrounding areas may experience economic benefits, since the flood might trigger business and orders that cannot be performed by the flood-affected companies.

Regarding the temporal scale, flood can cause long-term consequences, such as health effects, which are not captured if a too short time horizon of the damage assessment is chosen.

There are not official or widely recognized definitions for spatial and temporal scales. Messner et al. (2007) give recommendations for the choice of the appropriate approach.

5.4 Economic principles

In the assessment of economic flood damages, it is important to choose the opportune spatial and temporal scale, not to neglect any loss typology and to refer to damage data compatible with the information to be derived.

The choice in the **spatial and temporal scales** for the analysis depends on who is conducting the study and influences the results.

Molinari et al. (2013) underlined the difference between (i) financial evaluations, made by a private person or enterprise, in which the focus is the effect of hazard on personal profit while public affairs can be neglected and (ii) economic evaluations, in which the assessment of hazard impact on public (national or regional) welfare is central. This difference between financial and economic flood damage values has been illustrated in a research by Black and Evans (1999) and has been reported in the Multi-Coloured Manual (Penning-Rosewell et al., 2013), including a synthesis (which refers to economic and financial damages related to household flood losses) in a table (Table 2).

Table 2. Financial and economic residential flood damages (Penning-Rosewell et al., 2013).

Financial
Takes the standpoint of the individual household or organisation involved
Uses the actual money transfer involved to evaluate the loss or gain (e.g. if a household has a new-for-old insurance policy and they claim for a ten year old television, the loss is counted as the market price of a new television)
VAT is included as are other indirect taxes as they affect the individual household or organisation involved
Economic
Takes the standpoint of the nation as a whole – one person's loss can be another person's gain
Corrects the actual money transfer in order to calculate the real opportunity cost (e.g. in the case of the ten year old television, the real loss to the country is a ten year old television; the depreciated value of that ten year old television is taken as the loss
VAT is excluded, as are other indirect taxes, because they are money transfers within the economy rather than real losses or gains

These different approaches imply different choices of spatial scales and different results, because each analysis does not take into account a particular loss: the financial analysis neglects everything out of its interest; in the economic analysis the losses of a company may be balanced by the advantages of another, resulting in no net loss. The scale influence particularly this last type of analysis, because economic losses at a regional level can disappear at national one.

Merz et al. (2010) suggest to choose the time and spatial boundaries of the damage assessment in accordance with the time and spatial boundaries of the public policy project to be evaluated and to indicate any positive and negative transboundary impacts at least qualitatively in addition to the impacts assessed within the regional or executive boundaries.

Inside an analysis on indirect tangible damage assessment, it is important not to neglect the **costs for the emergency management**, especially when the analysis is aimed at a cost-benefit evaluation and its results can be completely altered otherwise. They include e.g. clean-up costs, evacuation, recovery and other emergency services costs, which could even exceed direct losses (Morselt et al., 2007; Pfurtscheller and Schwarze, 2008).

Another choice to be done that influences the damage analysis regards the value to assign to exposed items. When the flood occurs, the real value of durable consumer goods is a **depreciated value**, whereas the insurance companies often refer to substitution values in damage assessment, because "Old goods which are damaged during a flood are substituted by new, more productive or better performing ones" (Penning-Rowsell et al., 2003). This choice overestimate damages, because of the implied improvement in objects considered. Moreover, Merz et al. (2010) underline that the use of substitution costs is in contrast with the national accounting, that uses depreciated values for capital goods, based on a perpetual inventory of incoming and outcoming capital goods. The full replacement costs result in "values at risk" higher than the ones depicted in the national accounts. In the Multi-Coloured Manual approach for residential properties damage assessment, the depreciated value of the complete building including its inventories is determined according to replacement costs and market prices. Then, relative damage curves are multiplied for this value in order to derive absolute ones.

Finally, when considering capital goods, whose value consists in the the present value of the income flow it generates over the rest of its life span (Georgescu-Roegen, 1981), it is important to choice between **stock and flow value** to avoid double counting (Merz et al. 2010, Rose, 2004; van der Veen and Logtmeijer, 2005; Bockarjova et al., 2007). An alternative can be using one or the other value indifferently for different items, paying attention in clearly separating them (Messner and Green, 2007).

5.5 Flood damage assessment methodologies

A first distinction concerning damage assessment methodologies regards the analyses they address. Two macro-classes can be distinguished, in particular:

- post-flood damage analysis, implemented after the flood to estimate a focus event consequences (ex-post investigation);
- estimation of flood expected damages associated to projections of future scenarios (ex-ante investigation).

The first kind of analyses can be carried out through detailed post-event surveys, where the evaluation consists in the simple quantification of damages after the event, or through the use of pre-existing or ad-hoc derived models (e. g. damage functions), which may be grounded on historical data. In analyses ex-ante, instead, the use of models is inevitable.

When introducing the general classifications of damages in direct, indirect, tangible and intangible, it has been already outlined that the majority of damage assessment methods are developed for direct tangible damages estimation.

The general approach to direct tangible damages analysis foresees the adoption of damage functions. The EMA (2002) distinguishes two classes of damage functions: functions derived through averaging approach and stage-damage functions:

- the averaging approach uses an average loss per impacted dwelling, with average values for business premises based on the area of the structure;
- stage-damage functions (otherwise called stage-damage curves) model, instead, describes the relationship between the expected loss in the unit and the varying depth of the flood water (or the variation of other damage influencing variables).

Stage-damage functions have been introduced by White (1945, 1964) in USA and are today the most widespread instrument for direct damages assessment.

Indirect damages, instead, are generally derived from direct ones or, alternatively, adopting ad-hoc methods derived from other disciplines.

Finally, intangible ones are often neglected or their assessment refers to the only estimation of the effects of floods on people health (neglecting effects on the environment or cultural heritage).

In this sub-section is given an overview on damage assessment methodologies (synthetized in Figure 4), starting from indirect tangible and intangible damages, and arriving to direct tangible ones.

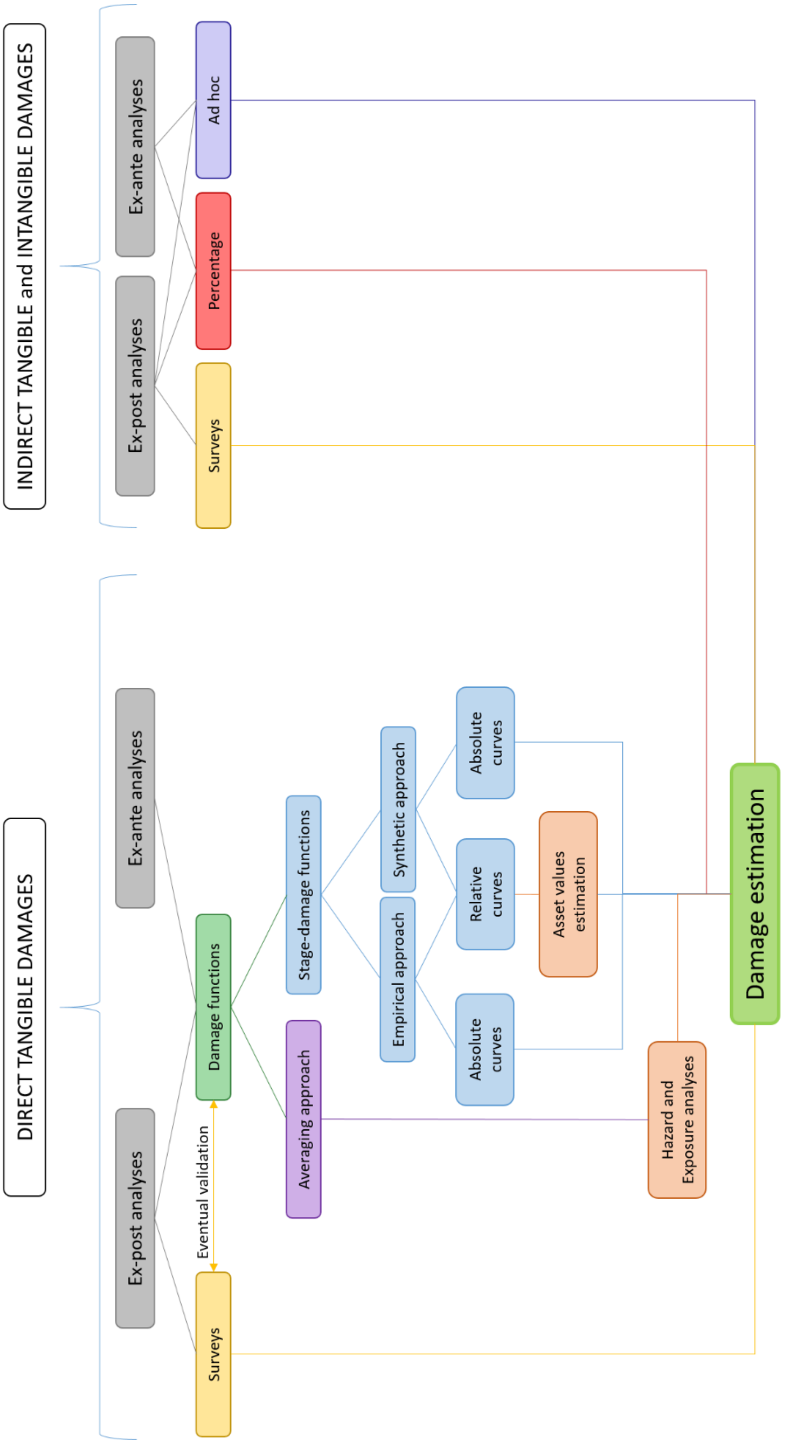

Figure 4. Overview on damage assessment methodologies.

Indirect tangible damages

When studying indirect tangible damages, the general approaches used are “implicit methods”, so called because they consist in the derivation of indirect damages starting from direct ones. In particular, they can be roughly estimated by means of percentages of direct damages (NR&M, 2002; NRE, 2000) or, such as happens in MCM (Penning-Roswell et al. 2013), by means of surrogate values (e.g. the cost of renting an equivalent home).

Alternatively, indirect damage estimation can be carried out by ad-hoc methods based on economics or other disciplines. Among these, input-output (I-O) and Computable General Equilibrium (CGE) modelling are the most frequently used. I-O models focus on production interdependencies and estimate the consequences of a specific impact on one or more economic sectors on other sectors of the economy. This is achieved by applying fixed input-output coefficients, which describe relationships between different economic sectors. Some examples of their application in flood impact assessment can be found in Van der Veen and Logtmeijer (2005) and Jonkman et al. (2008). CGE modelling uses an equation system to represent the demand for goods by consumers and the supply of goods by producers. Equilibrium constraints are used to solve the supply and demand requirements simultaneously. Rose and Liao (2005) used such a model to study the resilience of the water supply system following an earthquake in Portland, USA. Intermediate models between I-O and CGE are Input Output models with flexibility, as the Adaptive Regional Input-Output model, which was used to assess the indirect impact of flooding following Hurricane Katrina in Louisiana (Hallegatte 2008) or CGE models with reduced substitution elasticity, as in Rose et al. (2007).

Inside the indirect costs, specific methodologies have been developed for the estimation of business interruption costs. A method consist in applying a sector-specific loss value that represents the losses from added value, or the wage losses: in an example in Germany, it is the gross value added per employee per day, than multiplied by the number of employees and the number of days of disruption to estimate the total cost arising from business disruptions (MURL 2000). The arising challenge is the assessment of the length of business interruption. In a survey of 415 companies affected by the 2002 flood in Germany, Kreibich et al. (2007) found that the mean duration of business interruption was 43.1 days. Chatterton (2008) found that, for a major car manufacturing plant, significant flooding could lead to maximum 30 days of interruption, followed by 60 days before disruption ended completely. Seifer et al. (2009), studying flood events occurred in 2002, 2005 and 2006, found a correlation between the length of business interruption and (i) the impact variables such as water depths, flow velocity, duration of the flood, contamination, (ii) size of the company and (iii) an indicator representing the precautionary measures implemented by the company.

Intangible damages

The estimation of intangible damages, as their own definition suggests, raises so many questions that in most cases they are ignored. While in Multicriteria Analysis framework they can be included as non-monetary decision criteria or, in a Cost-Effectiveness Analysis framework, as a non-monetary target measure, in a Cost-Benefit Analysis framework, intangible costs have to be expressed in monetary terms (Meyer et al. 2013). This aspect rises the ethical objections on how to prize a life or an historical monument, or how to give value to the environment preservation and makes the evaluation difficult and subjective.

Another difficulty arises because of the lack of database and of literature examples that, although already present in general damage assessment, becomes even worse while studying intangible damages and the few data are mostly referred to the calculation of injuries, neglecting other typologies of these losses.

According to Hajat et al. (2005), the principal types of health impacts from flooding are:

- physical health effects sustained during the flood event itself or during the clean-up process, or from knock-on effects brought about by damage to major infrastructure including displacement of populations. These include injuries and the loss of life, as well as diseases linked to the flooding, e.g. diseases diffused because of water contamination.

- mental health effects, which occur as a consequence of the experience of being flooded and during the recovery process, and to people proximate to the flooding.

Jonkman and Kelman (2005), studying data from thirteen flood events from Europe and United States, resulting in 247 fatalities, analysed the causes and circumstances of these deaths in order to lay the foundation for the formulation of prevention strategies and the development of risk-to-life models. They saw that medical causes of death are the product of the amalgamation of hazard and vulnerability elements:

- the effects of flood hazards on people, that can be interpreted as “flood actions” (Kelman and Spence 2004), include forces, pressure, motion, chemical reaction due to contaminants, …;
- vulnerabilities of an individual potentially leading to death during a flood include age, gender, physical and mental actual condition, behaviour, swimming ability and experience, … .

The influence of flood actions is poorly documented, so Kelman and Spence focused their work on studying the influence of vulnerability ones to fatalities. The detailed results of this analysis is reported in their work. A significant result is that approximately two thirds of injuries were due to drowning and that people awareness, swimming ability and factors related to receipt of and compliance with warnings played an important role on this result.

These insights have been used to develop risk-to-life models. Jonkman et al. (2008) provided a comprehensive review of methods for the estimation of loss of life due to flooding and developed a method for the estimation of loss of life caused by large-scale flooding of low-lying areas. This model takes into account the characteristics of the flooding, the estimation of the number of people exposed (including the effects of warning, evacuation and shelter), and an assessment of the mortality of those people exposed to the flooding.

In Jonkman et al. (2008) and in Hammond et al. (2013) can be found in deep analyses on the variables influencing risk-to-life connected to floods. In Jonkman et al. (2010) and in Meyer et al. (2013), the analysis is extended including approaches for the estimation of loss of life due to different natural hazards.

Damage curves for direct tangible impacts assessment: a general overview

Although flood damages depend on many variables (see par xx), few studies include such factors in damage modelling: the majority of damage functions relate flood impacts to the only water depth, that's why they are also called depth-damage curves.

There are two main approaches for the derivation of depth-damage curves:

- empirical approach, in which are used damage data derived from ex-post assessments of actual past events (e.g. the FLEMO damage model from Thieken et al., 2008);
- synthetic approach (ex-ante analysis), in which damages are estimated for standardized property types, while the proportional damage is estimated by expert judgement(e.g. the MultiColoured Manual method from Penning-Rowsell et al., 2013). This is the so-called "what-if analysis", in which the question "which damage would you expect for different water depth?" is answered.

A combined use of the two approaches is possible, both extending empirical data with synthetic ones or validating synthetic curves through collected damage data. A table from Merz et al. (2010), with advantages and disadvantages of both approaches is here reported to better understand their potentialities and limits (Table 3).

Table 3. Advantages and disadvantages of empirical and synthetic flood damage models (Merz et al., 2010).

	Advantages	Disadvantages
Empirical damage models	Real damage information possesses a greater accuracy than synthetic data (Gissing and Blong, 2004). Effects of damage mitigation measures can be quantified and taken into account in damage modelling (Kreibich et al., 2005; Thieken et al., 2008). Variability within one category and qater depth is reflected by the data and uncertainty can be quantified (Merz et al., 2004).	Detailed damage surveys after floods are uncommon, so that models may be based on poor quality data (Smith, 1994). Paucity of information about floods of different magnitude and often a lack of damage records with high water depth require extrapolations (Smith, 1994; Gissing and Blong, 2004). Transferability in time and space is difficult due to differences in warning time, flood experience, building type and contents (Smith, 1994).
Synthetic damage models	In each building, damage information for various water levels can be retrieved (Penning-Roswell and Chatterton, 1977). Approach does not rely on information from actual flood events and can therefore be applied to any area (Smith, 1994). Higher level of standardisation and comparability of damage estimates.	High effort is necessary to develop detailed data bases (inventory method) or undertake large surveys (valuation survey method) to achieve sufficient data for each category/building type (Smith, 1994). What-if analyses are subjective, resulting in uncertain damage estimates (Gissing and Blong, 2004; Soetano and Proverbs, 2004). Mitigation actions are not taken into account (Smith, 1994). Premises within one classification can exhibit large variations which are not reflected by the data (Smith, 1994).

Gissing and Blong (2004) argued that empirical damage functions derived from real data are more accurate than synthetic ones. Anyway, the main obstacle in the development of flood damage functions is the lack of good quality databases.

Another distinction to do when talking about depth-damage curves is between:

- absolute damage functions, supplying directly the value of damage associated to each inundation depth;
- relative damage functions, expressing the damage as a share of the total unit value, varying with different inundation depths.

When using absolute functions, the estimated monetary damage caused by a given flood scenario results directly and no asset values are needed. On the other side, these functions need to be periodically re-calibrated because they depend on market values of individual structures and thus they are influenced by shifts in local economy, inflation, … Moreover absolute functions depend on the affected object value, so their transferability is limited and request another opportune calibration.

Relative damage functions, instead, allow for a better transferability in space and time, since they are independent of changes in market values. But they allow for a simple vulnerability analysis and assets' values are requested to complete the information and provide damages estimation (see section 3 of this chapter).

Merz et al. (2010) described the three steps in the calculation of direct tangible damage as:

- classification of elements ar risk,
- exposure analysis and asset assessment,
- susceptibility analysis (through the damage functions).

First, the elements at risk should be classified and pooled into homogeneous classes, whose detail depends on the available data and the scale of the analysis. Than an analysis of the assets and their exposure is necessary to identify and number objects at risk and, when using relative depth-damage curves, to estimate their value. Finally, a susceptibility analysis through the use of the functions can be conducted.

Stage-damage curves for buldings

Despite some stage-damage curves have been introduced for the estimation of damages to infrastructures, their classical application is to buildings' damages assessment.

The Multi-Coloured Manual distinguishes among residential, commercial and industrial properties. Among residential buildings, the MCM contains different depth-damage curves in function of properties age, types of buildings (detached, semidetached, flat, bungalow…) and the social status of residents.

In the Dutch Standard Method (Kok et al. 2004), damage assessment is carried out by using the formula:

$$S = \sum_{i=1}^{n} a_i n_i S_i \tag{2}$$

with:

- a_i damage factor category i,
- S_i maximum damage per unit in category i,
- n_i number of units in category i.

The results are considered to be applied for low flood-frequencies areas: they are incremented of 25% when referring to high-frequency flooded ones. Damage factors are derived from functions, one per category, which show their dependence from hydraulic parameters: because of this structure of the methodology, these functions are nothing more than relative depth-damage functions. The categories of buildings considered are companies and dwellings. Inside this last category it can be found single-family, low-rise, intermediate and high-rise dwellings; the first two are hypothesized to be in brickwork, the last two in concrete. These functions from the Standard Method are reported in Figure 5 and 6: the first one reports the curve for single family dwellings and farm, with the distinction of building's and contents' damage contribution; the second one reports the comparison among all the curves (single family dwellings and farms, low-rise, intermediate and high-rise dwellings).

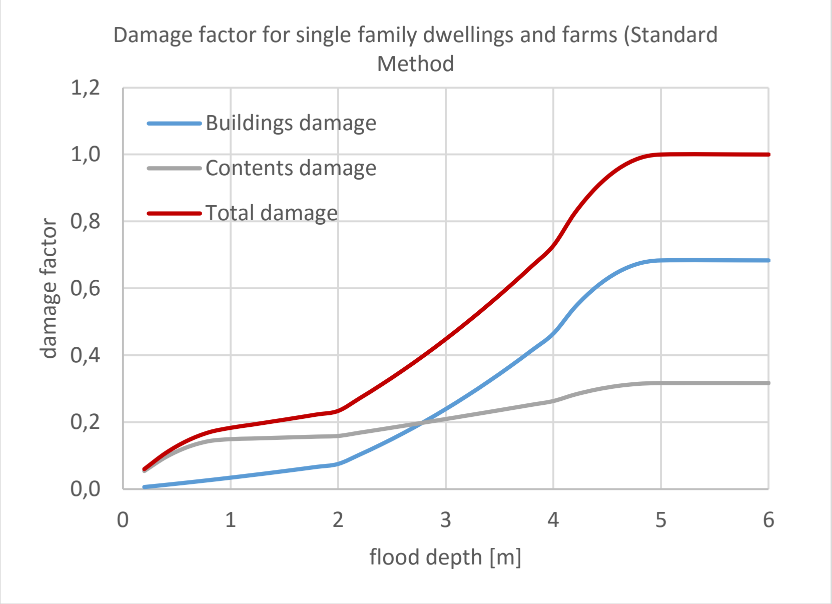

Figure 5. Damage factor for single family dwellings and farms according to the Standard Method (Kok et al., 2004), distinguishing the contributions of buildings and contents' damages, in the hypothesis of no storm or current.

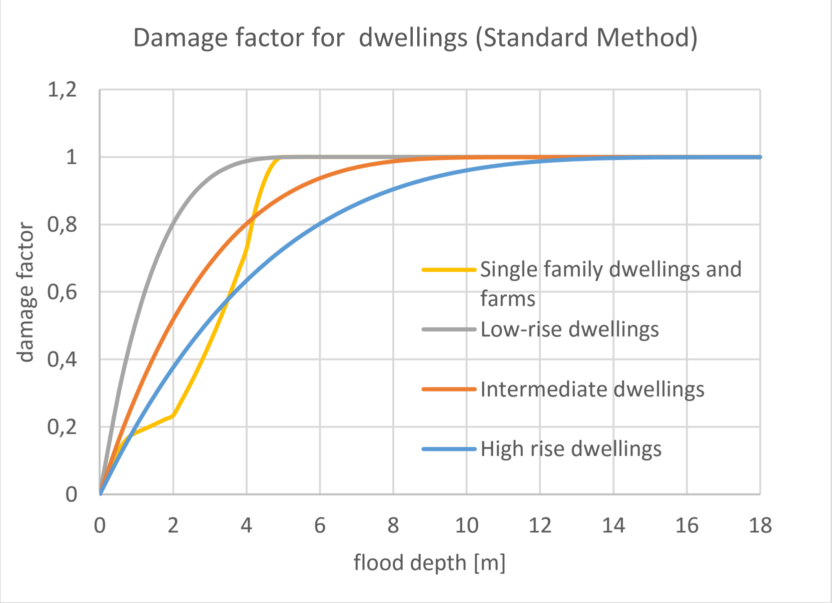

Figure 6. Damage factor for low-rise, intermediate and high-rise dwellings according to the Standard Method (Kok et al., 2004) in the hypothesis of no storm or current.

The U.S. Army Corps of Engineers developed depth-damage curves (USACE, 2003, 2000) through empirical approach, adopting data collected from major flooding that occurred in various parts of the United States from 1996 through 2001 under the Flood Damage Data Collection Program. The Institute for Water Resources of the USACE implemented this program to provide information from flood events to estimate reliable economic relationships for flood damage reduction studies. Generic damage functions for one-story homes, two or more story homes, and split-level homes either with or without basement, providing the damage as a percentage of structure value, have been developed. For each structure occupancy type, a content-to structure value ratio is defined too.

The German Flood Loss Estimation Model for the private sector FLEMOps+ (Thieken et al., 2008) was derived from the data collected in the aftermath of the 2002 flood event in Germany. Its loss functions consider as influencing variables: water depth; building type, distinguishing among one-family homes, (semi-)detached houses and multifamily houses; low/medium or high building quality; none, good or very good precaution implemented; none, medium or heavy contamination of flood water. The functions have been first derived at micro-scale (building scale as the one of collected data) and, after, adapted for meso-scale (land-use unit) thanks to statistical information provide by INFAS Geodaten GmbH (2001).

In Meyer et al. (2013) it can be found a table in which general methods for direct costs evaluation are presented. An extract of the table listing worldwide (single-parameter and multi-parameter) models for damage functions is reported in Table 4. It includes damage functions introduced for coastal flooding and Alpine hazards like flash floods, debris and mud flows, landslides…

Table 4. Applications and examples on single- and multi-parameter susceptibility function (extract of a table from Meyer et al. 2013 on models, applications and examples for the assessment of direct costs).

General method	Specific method	Application and/or examples
Susceptibility function	Single-parameter models (based on single hazard impact parameter)	Floods: Model of ICPR (2001); Model of MURL (2000), adopted by Glade (2003); Model of Hydrotec (Emschergenossenschaft and Hydrotec 2004) Coastal hazards: Reese et al. (2003)
		Droughts: Corti et al. (2009)
		Alpine hazards: Fuchs et al. (2007), Huttenlau (2010), Totschnig et al. (2011)
	Multi-parameter models (based on several hazard impact and/or resistance parameter)	Floods: HAZUS-MH (FEMA, 2011; Scawthorn et al., 2006); FLEMOps and FLEMOcs models (Apel et al., 2009; Elmer et al., 2010; Kreibich et al., 2010; Thieken et al., 2008); Model of Multi-Coloured Manual (Penning-Roswell et al. 2013); HIS-SSM (Kok et al., 2004); Model of Maiwald and Schwarz (2010)
		Coastal hazards: FEMA (2011), HIS-SSM (Kok et al., 2004), Nadal et al. (2010)
		Alpine hazards: BUWAL (1999), Keiler et al. (2006), Holub et al. (2012)

At a local level, an attempt to develop a flood damage function for the residential sector has been made by Luino et al. (2006). Using data obtained from 100 flooded buildings in one event in 2002 in the small Boesio catchment area in the Lombardy Region, the curve was obtained by interpolation across the plotted couples of flood depth and damage. Freni et al. (2010) also interpolated depth–damage data to test the prediction accuracy of flood risk estimates by comparing uncertainty deriving from damage models and that due to hydraulic modelling (more details on the adopted data in section 4.4 of this chapter). The problem with interpolation techniques is the high level of uncertainty in the depth–damage curves and the fact that they can be deemed reliable only for the specific context for which they were obtained, as stated by Luino et al. (2006).

Depth-damage for other sectors

Because of the success in the use of damage functions for the assessment of private buildings damages, different attempts of extending this instrument in the evaluation of other direct damages are present in literature. In particular, this section shows an overview of damage functions adopted for the estimation of (i) damages to vehicles, (ii) direct damages to infrastructures, (iii) damages to buildings in the commercial sector.

In USA, as part of residential post-flood damage survey, inside the Flood Damage Data Collection Program, data were collected for vehicles kept at residences in ten communities that experienced major flooding. Depth-damage functions were determined using flood victims' self-reported assessments of vehicle values and damage and the depth of flooding above the wheelbase for each vehicle. Damage functions were computed for five types of vehicles based on a sample of 640 vehicles. Regression analysis was used to compute the damage functions. As reported in USACE (2009), the regression equations for all types of vehicles were highly significant.

An important challenge in the assessment of direct tangible losses regards the analysis of damages to infrastructures, often neglected. The difficulties in evaluating direct damages to infrastructure are many and mainly caused by their wide variety and their interconnections: infrastructures include transport services, power, water, emergency services, telecommunications… and are crossed each other (damages to electricity supply can cause interruption in telecommunications networks or in water supply).

In the Netherlands, the Standard Method (applied at national scale) includes damage functions describing flood impacts to roads, railways, motorways, pumping stations and purification plants (Meyer and Messner 2005, Kok et al. 2004).

In the US HAZUS too are introduced depth-damage functions (derived from experts’ judgment) for lifelines such as water, electric, roads and railroads (Scawthorn et al., 2006). In Hammond et al. (2013)

are cited other methodologies for infrastructures' damages estimation derived from economic techniques and studies on infrastructures' interconnections.

Kreibich et al. (2010) in Germany developed the Flood Loss Estimation MOdel for the commercial sector (FLEMOcs), collecting data from affected companies after the flood in August 2002, and after the floods in 2005 and 2006. The model uses relative damage functions distinguishing damages at buildings, equipment and goods, products, stock. It considers five factors influencing loss ratios: as impact factors water depth and contamination; as resistance factors precautionary measures, size of the company and sector. As the equivalent model for residential buildings (see previous paragraph and refers to Thieken et al., 2008), it can be applied to the micro-scale, i.e. to single production sites as well as to the meso-scale, i.e. land-use units.

Other models adopting damage functions for the commercial or the industrial sectors are the US-model HAZUS-MH (FEMA, 2003), the UK model presented in the Multi-Coloured Manual (Penning-Roswell et al., 2013), the MURL (MURL, 2000), the Hydrotec (Emschergenossenschaft & Hydrotec, 2004), the RAM model (NRE, 2000), model of ICPR (ICPR, 2001), model of LfUG Saxony (LfUG, 2005). Much details and comparisons can be found e. g. in Kreibich et al. (2010), Merz et al. 2010.

4.3 *Damage databases and uncertainties*

In respect to other aspects of flood risk management, flood damage assessment is still a challenge and one of the main reasons of this is the lack of consistent, high-quality, official damage databases.

The HOWAS database, held at the Bavarian Water Management Agency, contains information about the flood damages caused to buildings by nine floods between 1978 and 1994. Buildings are classified into six economic sectors: private households, public infrastructure (e.g. transformer station, schoolhouse, fire station), services sector (e.g. supermarket, restaurant), mining and building industry (e.g. civil engineering, carpentry, installers workshop), manufacturing (e.g. beverage industry, metal processing, wood processing) and buildings for agriculture, forestry and horticulture. HOWAS moreover distinguishes among damage to building structure, damage to fixed inventory and damage to movable inventory.

A different kind of database consists in the ensemble of damage curves reported in the MCM (Penning-Roswell at al., 2013): it contains data synthetically derived, in particular absolute damage functions. One of the disadvantages in absolute function is the quasi-impossibility in transferring them to other contests: the MCM curves express damages in pound sterling without any reference to the economic value of the affected buildings, thus linking them to the contest for which have been derived.

The Centre for Research on the Epidemiology of Disasters (CRED) in Brussels created, with the initial support of the WHO and the Belgian Government, the EM-DAT database, which "*contains essential core data on the occurrence and effects of over 18,000 mass disasters in the world from 1900 to present. The database is compiled from various sources, including UN agencies, non-governmental organisations, insurance companies, research institutes and press agencies*" (EM-DAT website). Unfortunately, as many of the other accessible data sets, it contains damage data that have already been aggregated to a regional or national level. This makes them unusable at minor scales.

Another limit in the utilization of flood damage data could be their aggregation in predetermined time intervals. In the U.S., the National Weather Service (NWS) collected historical records of flood damage occurred between 1926 and 2003 (Pielke et al., 2002; UCAR, 2003). The data collected, in particular, are the annual total damage estimates for the U.S., useful for studies on annual total damage, but unsuitable for analysis at shorter temporal scales (such as the estimation of single flood event losses).

Last but not least, the users of these data should always verify their accuracy, as sources of inaccuracy are multiple and difficult to estimate (Pielke et al. 2002; Merz et al., 2004).

Meyer and Messner (2005), interviewing national experts responsible for the application of flood damage evaluation, reported the need for more consistent and complete database among the main uncertainty causes in damage assessment.

4.4 *Available flood damage data in Italy*

The Italian National Research Council (CNR), in 1989, set up the AVI project (Guzzetti et al., 1994), with the aim of collecting data and information that could be found in historical, municipal, and private archives and newspapers to develop a catalogue of disasters caused by extreme hydrometeo-geological conditions, including floods, over the period between 1918 and 1990. Unfortunately, the limits of this database are enormous. The information is provided, in fact, in a narrative form and often is not or badly georeferenced. Their utilization in the development or validation of damage functions is hard and require the collection of additional data (if available) and the reorganisation of the available ones. Even the impact variables are often difficult to derive because of the lack of data on their influencing factors (precipitations, discharges, …).

At the regional level, as in Italy no insurance policy covering natural hazards to residential buildings exists, information on flood damages is collected by the municipalities in order to apply for reimbursements: the Regional authorities collect these data and ask compensation to the central government (possible if a state of emergency has been declared by the National Civil Protection Department). This division of responsibilities cause a general subjectivity in how to collect data, either at regional or municipal level, causing inconsistencies among databases.

Data occurred in different sector, moreover, are saved in separate archives and managed by different offices, thus increasing subjectivity. Indirect damage are neglected in Regional collection, as they are not subject to compensation.

Locally, in Lombardia Region, the RaSDa (Sistema per la Raccolta delle Schede Danni) database has been derived by the introduction of a standard methodology for damage collection after disasters (Molinari, 2010, Molinari et al. 2014). It distinguishes damage occurred to private or public facilities (in this second case, another distinction is between damage to infrastructure and damage to buildings). Damage to contents is included in buildings’ one (either for public or private buildings). A lack in this database is the absence of hazard data, which may however be obtained from public technical agencies, monitoring and forecasting centres and even research centres: the resulting problem to face would be the uncertainties deriving from the attachment of data manipulated by different bodies.

As reported in Molinari et al. (2014): “*the existing large-scale databases in Italy are too poor to support a comparison between the results that would be obtained using damage functions from the literature and actual damage recorded in past events. At least one of the three main factors to be related – hazard, vulnerability, or damage – is always missing or too imprecise to develop a comparison*”.

Freni et al. (2010) confirmed this conclusion by comparing the intrinsic uncertainty connected to the construction of the depth-damage function to the hydraulic model uncertainty. Thanks to a monitoring campaign coordinated by the municipality of Palermo after ten (high frequency/low damage) to flood events occurred in the historic city centre between 1993 and 1997, damage data from fire brigades and insurance companies were collected. The integration between the damage curves and the hydraulic model resulted in increased uncertainty in respect to the hydraulic model alone, such that “*the advantages provided by detailed (hydraulic) models may be largely absorbed by the uncertainty in damage estimation*”.

Chapter 2 – Methodology

1. Introduction

In this work a methodology for flood risk assessment, based on the definition of Exposure classes and the derivation of flood Vulnerability curves for buildings, is presented (see Figure 7). The goal is to describe flood consequences, or rather flood risk, in those watersheds where vulnerability data don't exist or their quality makes theme unreliable. The methodology has been developed in four steps.

At first (section 2 of this chapter), an hydraulic modelling has been necessary to derive the hydrodynamic characteristic of the flood event studied; the model used is a 2-D model developed by Aronica et al. (1998). It integrates classical hydraulic equation by using a finite element technique with triangular elements. In order to minimize the error between the observation and the prediction data, the model has been calibrated with reference to floodplain and river channel roughness (assumed the most important parameter controlling the inundation extent). Calibration was performed through Monte Carlo simulations using both inundation depths and flow velocities.

The second step (section 3 of this chapter) has been the particularization of the Exposure classes provided in the Flood Risk Plan for Sicily (Regione Sicilia 2004). In fact, in order to limit the in depth economic studies required to derive the monetary value of buildings in areas at risk, the entity variable of risk equation has been substituted with their exposure, which is a nominal value dependent on their strategic, functional and economic value. Starting from the Exposure classes provided by the Sicilian Plan, a detailed building Exposure classification has been deduced at the micro-scale.

The third step (section 4 of this chapter) consisted in the derivation of vulnerability curves for different buildings in Sicilian territory through a synthetic approach. This approach allowed obtaining the curves despite the lack of damage data from previous events. To make the curves as generic as possible, instead of referring to building typologies with a specific geometry inside, it was considered the damage suffered by building's elements and hypothesized the substitution cost of each element to derive its weight respect to the total substitution costs. To describe the proportional damage, a questionnaire was submitted to a team of experts.

At last (section 5 of this chapter) the vulnerability assessment for different Exposure classes, referring to a flood event occurred in the town of Barcellona Pozzo di Gotto (located in North-East Sicily, Italy), was carried out. The results has been reported both in a map and in an Exposure-Vulnerability matrix, allowing an immediate understanding of flood consequences. The goal was to obtain an exposure-vulnerability crisscross classification, as both these variables play complementary roles in flood risk assessment and none of them should be neglected.

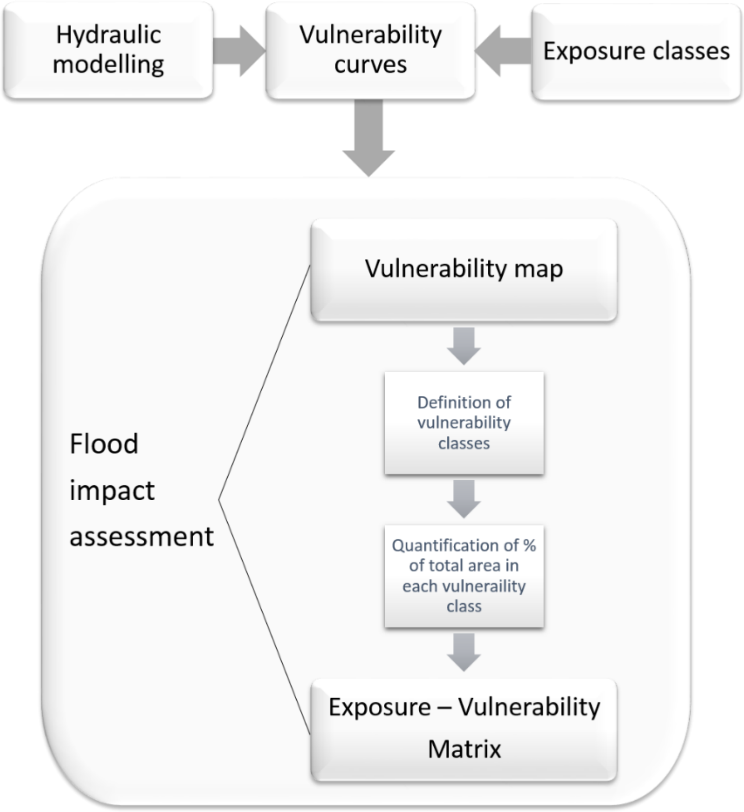

Figure 7. Layout of the proposed methodology.

2. Flood hazard mapping (models, uncertainty, calibration)

In this section, a detailed description of the hydrological and the hydraulic modelling approaches for the derivation of the variables connected to flood hazard.

2.1 Rainfall-Runoff modelling

There are several methods and model to evaluate the hydrological response of a catchment. A general distinction can be done between (i) *physical* models, which represent a real system at a reduced scale or through another physical system with similar properties, and (ii) *abstract* models, which represent the system through equations linking input and output variables. These variables can be function of space and time, and can be deterministic, probabilistic or random. According to

Chow et al. (1988), so, three decisional levels should be accounted: randomness (or not), time-varying and space-varying of the variables.

The possibility of choosing models with different degree of complexity is one reason why there is no commonly agreed modelling strategy. Nevertheless, depending on data availability and measurements techniques, two are the classical basic approaches used to gain the hydrological input for the hydraulic model:

- *statistical analyses* of discharge data, providing a single value of the flood peak for a selected return period;
- *Rainfall-Runoff (R-R) models,* providing the flood hydrograph (that shows the flow rate as a function of time at a given location on the river) for selected return period, with peak discharge, flood volume and shape of the hydrograph.

A synthesis of the available typologies of hydrological models is shown in Figure 8.

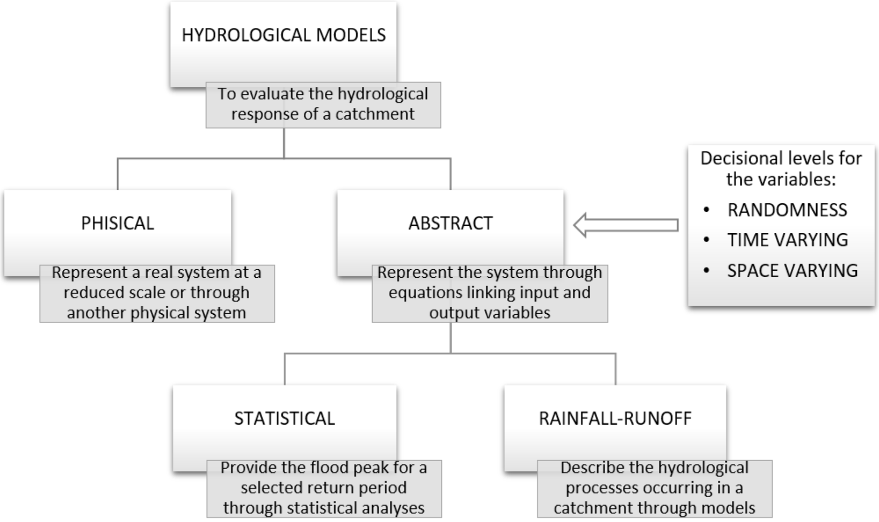

Figure 8.Overview of hydrological models.

A detailed description of these approaches is beyond the scope of this work: here a brief reference to the R-R one (adopted in this study), focusing on the particular methodologies used.

The R-R models try to describe the complex hydrological processes occurring in a catchment from the formation of rainfall to the final streamflow. A key component of the study is the *excess rainfall hyetograph* (ERH), which is a plot of excess rainfall depth or intensity as a function of time. To derive it, precipitation frequency analyses are required: the output consist in the computation of the amount of precipitation falling over a given area in a duration of d minutes with a return period T.

In particular, it can be determined from rainfall hyetograph through different methods for the separation of effective rainfall from total one. The model used in this work is the Curve Number Model (SCS-CN), developed by the United States Department of Agriculture (USDA), Soil Conservation Service in 1972, that is a conceptual method to determine the excess rainfall as a function of soil characteristics (like antecedent moisture conditions).

To describe the flow routing and derive the final hydrograph, a general choice can be done among:

- *black box* models;
- *conceptual models* (describing the hydrology of a drainage basin from rainfall to stream discharge as several interconnected subsystem, each representing a certain component in the processing of a hydrologic event);
- *physically based models*, which seek to describe each part of the hydrological sequence as a set of precise mathematical equations which rigorously describe each process.

Here a conceptual model was chosen: a distributed unit hydrograph with climatic dependencies.

2.2 Hydraulic modelling

The description of processes taking place inside a catchment and, in particular, along the floodplains can be carried out thanks to flood inundation models of different complexity. They provide different information, the most important of which are flood and flow water depths, velocities and flood extent.

Hydraulic models can be classified according to the number of dimensions in which they represent the flow processes. In particular:

- one-dimensional (1D) models describe the flow's mono-dimensional routing in the down-valley direction;
- two-dimensional (2D) models describe the phenomena in two dimensions, assuming uniformity condition in the third one;
- three dimensional (3D) models consider each dimension, but they require a huge computational effort and are not commonly applied;
- coupled 1D/2D models are popular as they combine computational efficient 1D models, suitable for the simulation of flow in channels, with 2D models, for the simulation of floodplain flows.

Two-dimensional models are necessary when lateral flow velocities are not negligible and the inundation extent varies dynamically in time: this happens when flow is not confined in well-defined channels, but moves overbank in alluvial zones or urbanized areas.

These models typically integrate the Reynolds Averaged Navier-Stokes equations and in particular use the St. Venant equations, first developed by Barré de Saint-Venant (1871).

Even if examples of solution of the full two-dimensional models exist (e.g. Gee et al., 1990; Bates et al., 1998; Di Baldassarre et al., 2006), simplified models (see e.g. Molinaro et al., 1994; Aronica et al., 1998; Tucciarelli and Termini, 2000; Hunter et al., 2007) are often preferred because of their easier implementation and lower computational effort requested. Moreover, the use of sophisticated models is rarely supported by consistent input data and boundary hypothesis, such that their contribution in terms of reliability can be greatly reduced. Finally, even if simplified models may lead to local inaccuracies, they have been successfully tested against analytical solutions. A wide inherent bibliography can be found in Hunter et al. (2007).

All these equations cannot be solved analytically, but a discretization method which approximates the differential equations by a system of algebraic equations is required: the approximations provide results at discrete locations in time and space. The most important approaches to obtain numerical solutions are

- *finite difference* (Smith, 1978) approaches,
- *finite element* (Zienkiewicz and Cheung, 1975) approaches,
- *finite volume* (Hirsch, 1988) approaches.

Following a description of the model used in this study and the calibration methodology is given.

2.3 MLFP-2D hydrodynamic model

To simulate flood propagation, a 2D model (Aronica et al., 1998) based on DSV equations has been used. The equations can be expressed as:

$$\begin{aligned}
&\frac{\partial H}{\partial t}+\frac{\partial (uh)}{\partial x}+\frac{\partial (vh)}{\partial y}=0\\
&\frac{\partial (uh)}{\partial t}+gh\frac{\partial H}{\partial x}+ghJ_x=0\\
&\frac{\partial (vh)}{\partial t}+gh\frac{\partial H}{\partial y}+ghJ_y=0
\end{aligned}\tag{2}$$

where $H(t,x,y)$ is the free surface elevation, u and v are the x and y components of flow velocity, h is the depth of debris flow, J_x and J_y are the friction terms in the x and y directions.

The friction terms are represented through the classical Manning-Strickler formulation and can be expressed as

$$J_x=\frac{n^2 p\sqrt{p^2+q^2}}{h^{10/3}};\quad J_y=\frac{n^2 q\sqrt{p^2+q^2}}{h^{10/3}}\tag{3}$$

The model equations are solved by using a finite element technique with triangular elements, able to reproduce the complex topography of the built-up areas. Blocks and other obstacles are treated as internal islands within the triangular mesh covering the entire flow domain, while overfall structures as levees are modeled splitting the original domain into several subdomains connected by vertical discontinuities.

Inside each element, it is assumed: the continuity and linear variation of the free surface elevation; the constancy of the unit discharges *uh* and *vh*, in the *x* and *y* directions.

Model input and output

The model requires detailed topographic information, in particular: topographical map preferably with a scale of 1:10000 and lower, a high spatial resolution DEM and data set about the river topography (a number of cross sections with bed elevations, channel widths and roughness coefficients are useful to improve the mesh descriptive capability in those parts of floodplains (Horritt and Bates, 2001)).

The spatial and temporal variation of flood discharge should be included as a source term (upstream boundary condition), while dry bed conditions are assigned in the computational domain as initial conditions.

The computed water surface elevations are always continuous both in time and in space, and appropriate boundary conditions are always given by the incoming unit flux along the upper part of the boundary and the water surface elevation along the lower part of the same boundary (Aronica et al., 1998).

2.4 Model calibration

Flow resistance in hydraulic models is usually specified through roughness parameters, assigned in 1D models at each computational segment or at each grid element or cell in mixed 1D/2D and 2D models). Different authors (e.g. Pappenberger et al., 2005) found the geometry and the roughness parameter to be the most important elements affecting inundation extent and flow characteristics.

The simpler method to select roughness coefficients is assigning them basing on the nature of the channel and floodplain surface: literature offers many examples of tables or analytical numerical relationships derived from experimental work (e.g. Chow, 1959, Kutja and Hong, 1996, Armanini, 2005).

Actually, roughness coefficients do not represent just channel and floodplain surface roughness in a model: they describe also turbulent momentum losses not explicitly modelled (Werner et al. 2005). Moreover, roughness coefficients often have to compensate (i) insufficient model setup, (ii) uncertainties related to the approximation of the real geometry and (iii) numerical approximations associated with the discrete solution of the flood routing equations (Romanowicz and Beven, 2003, Marks and Bates, 2000, Werner et al., 2005).

The roughness parameters required by the model become thus “effective” rather than “real”. These “effective” roughness parameters lack a physical interpretation even outside the model structure within which they were calibrated (Beven, 2000).

Because of their role, for the Monte Carlo analysis, friction owing to floodplain and river channel roughness was assumed the most important parameter controlling the inundation extend. Inside the model, it is possible to assign to each triangular element one constant roughness coefficient. The domain can be so divided into regions with a constant value inside: two principal regions were chosen, floodplain and river. An ensemble average roughness coefficient was assigned to each one of them (thus approximating the true heterogeneous roughness with a homogeneous one causing similar responses).

The aim of the model calibration is to minimize the error between observation and predictions. Traditionally, hydraulic models have been calibrated using water levels of discharges recorded at the downstream outflow of the model. Because of the limits in this approach (Aronica et al, 1998a, 2002, Bates et al., 2004; Fabio et al, 2010), always more frequently the extent of the inundation area, derived from post-event shoreline surveys, aerial photos SAR data or LIDAR survey (Hunter et al, 2007), are used for model calibration.

Here, because of the numerous variables recorded during the November 2011 event (56 water depths within the flooded area and 2 flow velocities within the river channel), the measured variables to be compared to the simulated to calculate the residuals have been the water depths (WD) and the flow velocities (VEL).

Then, two objective functions (Residual Sum of Squares (SSR) and the Root Mean Square Error (RMSE)) that measure the discrepancy between observations and model outputs were defined, and the algorithm adjusts the parameter values until a convergence criterion is reached. Some assumptions regarding the statistical distribution (typically unknown) of the output data errors should be made.

Results of model calibration are reported in chapter 3, section 5.2.

3. Exposure assessment

The Exposure variable incorporates a global estimation of buildings' value: it depends on their economic value, but also on their social functions, their indirect involvement in economic losses and the population density of the area in which they are located.

This variable allows to distinguish between structures with same value but located in zones with different population densities and to define a scale of importance for public buildings based on their function rather than on their value. In this way, it is possible to establish a priority in protection strategies, both addressing the resources in most densely populated area or in a specific buildings' functional class (e.g. schools).

The starting point for Exposure classification in this study was the Sicilian Risk Plan approach (see chapter 1, section 4.2). It contemplates four Exposure classes, as in Table 5.

Table 5. Classes of Exposure according to Flood management Plan for Sicily (Regione Sicilia 2004)

CLASS	DESCRIPTION
E1	Sparse houses - Sports and recreational facilities - Cemeteries - Low technological agricultural settlements - Farming settlements.
E2	Technological infrastructures with secondary importance or dedicated to limited geographical area (aqueducts, sewers, electricity networks, telephone networks, depurators …) - Secondary roads (municipal roads not intended as escapes) - High technological agricultural settlements - Protected natural areas (or bonded by the law).
E3	Small inhabited - Railways - Primary roads and escapes - Civil Protection areas (waiting, shelter and gathering areas) - Technological infrastructures with primary importance (mains network and pipelines) - Cultural, architectural and archaeological asset under legal bond - Industrial and craft settlements - Plants (D.P.R. 175/88).
E4	Towns - Significant public buildings (schools, churches, hospitals, etc.).

Starting from this wide classification, each class was divided in subclasses containing each one elements with the same destination use. The second step consisted in the particularization of residential and public buildings in order to establish a scale among them, depending on their economic or strategic value.

What has been obtained, in particular, is a detailed classification of elements at risk, identified through a triple index. The first number refers to the membership class considered in the Sicilian Flood Risk Plan; the second one is relative to the Plan sub-categories; the third one details element per element inside sub-categories in function of their economic or strategic value: this level of detail enables to perform a vulnerability analysis at building scale.

Table 6. Proposed Exposure classification.

CLASS	DESCRIPTION	ELEMENTS AT RISK		
E1	Sparse houses - Sports and recreational facilities - Cemeteries - Low technological agricultural settlements - Farming settlements.	Sports and recreational facilities		**E1.1**
		Cemeteries		**E1.2**
		Farming settlements		**E1.3**
		Low technological agricultural settlements		**E1.4**
		Sparse houses	Villas	**E1.5.1**
			Flats	**E1.5.2**
			Single houses	**E1.5.3**
E2	Technological infrastructures with secondary importance or dedicated to limited geographical area (aqueducts, sewers, electricity networks, telephone networks, wastewater treatment plant, …) - Secondary roads (municipal roads not intended as escapes) - High technological agricultural settlements - Protected natural areas.	Technological infrastructures with secondary importance or dedicated to limited geographical area	Aqueducts	**E2.1.1**
			Sewers	**E2.1.2**
			Electricity networks	**E2.1.3**
			Telephone networks	**E2.1.4**
			Depurators	**E2.1.5**
		Secondary roads		**E2.2**
		High technological agricultural settlements		**E2.3**
		Protected natural areas		**E2.4**

E3	Small inhabited - Railways - Primary roads and escapes - Civil Protection areas (waiting, shelter and gathering areas) - Technological infrastructures with primary importance (mains network and pipelines) - Cultural, architectural and archaeological asset under legal bond - Industrial and craft settlements - Plants (D.P.R. 175/88).	Small inhabited	Detached houses	**E3.1.1**
			Villas	**E3.1.2**
			Farmhouses	**E3.1.3**
			Single houses	**E3.1.4**
		Supermarkets and warehouses		**E.3.2.0**
		Industrial and craft settlements	Flats	**E3.2.1**
			Box/Garage	**E3.2.2**
			Sheds	**E3.2.3**
			Single houses	**E3.2.4**
		Railways		**E3.3**
		Primary roads and escapes		**E3.4**
		Civil Protection areas	Waiting areas	**E3.5.1**
			Shelter areas	**E3.5.2**
			Gathering areas	**E3.5.3**
		Technological infrastructures with primary importance (mains network and pipelines)		**E3.6**
		Cultural, architectural and archaeological asset under legal bond		**E3.7**
		Plants		**E3.8**

E4	Towns - Significant public buildings (schools, churches, hospitals, etc.).	Significant public buildings	Hospitals	**E4.1.1**
			Schools	**E4.1.2**
			Town hall and municipal offices	**E4.1.3**
			Churches	**E4.1.4**
		Civil Protection areas and offices	COC - UCL - COM CP and Police offices	**E4.2**
		Residential buildings	Detached houses	**E4.3.1**
			Villas	**E4.3.2**
			Flats	**E4.3.3**
			Box/Garage	**E4.3.4**
			Farmhouses	**E4.3.5**
			Single houses	**E4.3.6**

The different residential buildings' typologies refer to the statistical data on residential buildings' cost: the buildings' type presents in the territory under study were the only considered, but the Exposure table is easy to update for next studies.

The Civil Protection areas have been established for their strategic importance during and after an eventual catastrophic event.

4. Definition of vulnerability curves for buildings

The basic idea of this study was the derivation of relative vulnerability functions for those sites where both damage data and on-site building inspections are lacking.

Final aim in the derivation of vulnerability curves was to describe possible damages occurring after fluvial floods in urbanized area and to make the curves as generic as possible. While referring to fluvial floods, often characterized by low velocities, another initial condition was to neglect structural damages to the buildings and to consider what happens to non-structural building components.

As described in section xx, the first step in synthetic approach is to introduce the building typologies for which derive the curves: buildings are usually distinguished at first in function of their use, than in function of their structural features (such as materials, numbers of floors, extension, geometry, age, …). This implies strong hypothesis on the buildings' structure and the incorporation of each building presents in the study areas inside these standard pre-defined models.

To make our curves as generic as possible it was so decided, instead, to consider the damages suffered by buildings' (non-structural) components a to hypothesize the substitution cost of each element to derive its weight respect to the total substitution costs. To describe the proportional damage relative to each element, a questionnaire was submitted to a team of experts, in particular a team of civil engineers working in Sicily area.

The first step of the analysis consists of deciding which buildings' classes we want to include in the analysis: this distinction is just referred to the buildings' type, because their function has been already considered through their exposure. The same curves can be used for buildings with the same constructive features, even if they have different functions, such as residential or commercial. On the other side, different curves should be used for buildings with the same functions but with different features.

We considered concrete buildings without basement, with associated poor, medium or rich finishes: rich finishes should be associated to the richest buildings' types (like villas and cottages); medium finishes should be associated to medium buildings (like flats and single houses inside towns); poor finishes should be associated to detached houses and single houses in villages (Figures 9-13).

Figure 9. Example of buildings categorized as "poorly finished".

Figure 10. Example of building categorized as "intermediate".

Figure 11. Example of building categorized as "intermediate".

Figure 12. Example of building categorized as "richly finished".

Figure 13. Example of building categorized as "richly finished".

Regarding the conservation status, it should be important in quantitative analysis, but this is a qualitative one in which substitution costs have been used to describe the relative value of each component. Moreover, these values have been considered only in order to understand which weight has the substitution cost of a component in respect to the total substitution cost of them all: in this comparative view, it is important to uniform the referring conditions and apply the same hypothesis to every element.

After the definition of these conditions, it must be decided which elements should be studied, in order to prepare the questionnaire for the experts. In this work, we studied the damages suffered by: floors, walls, doors and French windows, windows, wiring, water plant, gas plant and services. Their substitution prices should be taken from the official price lists and depend on their quality and materials, which in turn are derived from the finishes' class. For example, doors in poor houses are hypothesized to be hollow wooden, while in rich ones are supposed to be in solid wood: they will have different substitution costs, with different weigh in respect to the total costs; they will also suffer different damages for the same water depths. Another last condition investigated is the difference between short duration and long duration events: each of these conditions is described by its own curve.

Once that all these initial condition are defined, a team of expert is asked to describe, everyone according to his experience, how each component suffer damages in all the illustrated structures: the result is a series of "partial" vulnerability curves, one for every building element in a particular combination of finishes class and event duration.

The sum of the partial curves relative to the elements of a building type, each one multiplied for its weight, gives two total vulnerability curves for that building: one for short and one for long duration hypothesis. For a better description of the entire process for the definition of curves, a scheme is shown in Figure 14.

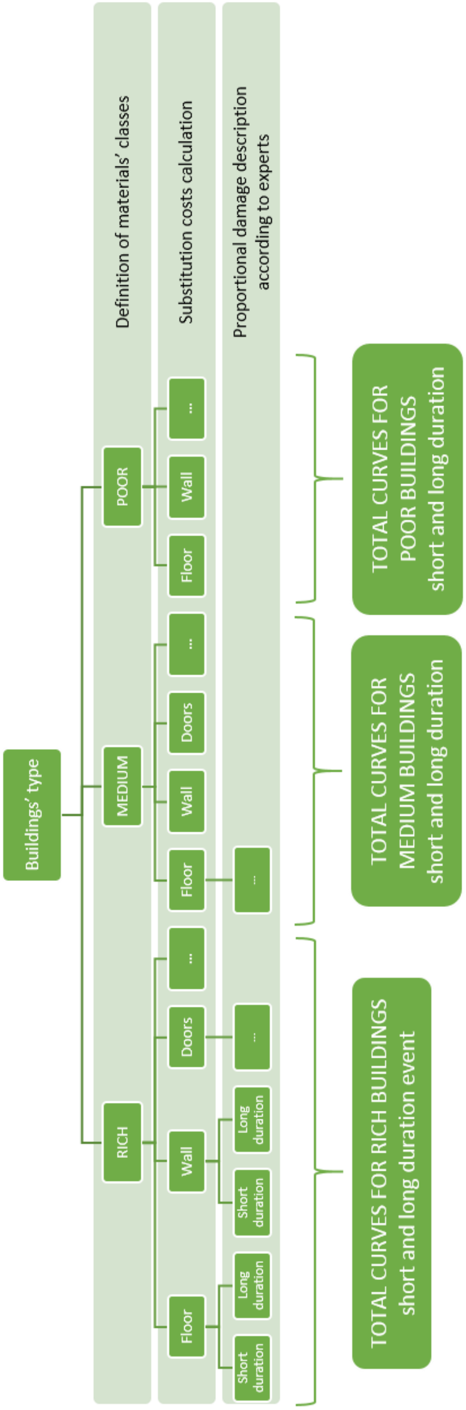

Figure 14. Scheme of the synthetic approach developed for the derivation of vulnerability curves.

A discussion apart needs to be done regarding the vulnerability curves for commercial activities. The majority of them is located in structures whit the same materials and building characteristic of residential constructions: the same vulnerability curves can be so used, because in the general analysis their exposure class will play the role to distinguish them from each other.

While considering supermarkets and stores, instead, the role played from the goods stored becomes fundamental. For these typologies, a double distinction has been made: on one side, they have their own exposure class; on the other side, a vulnerability range varying linearly from 0 to 1, while the water depths vary from 0 to 60 centimetres has been considered. The reason for this last choice is due to the fact that it seems plausible that when the water depth reach the height of 60 centimetres, the goods and the machineries (like fridges) contained in supermarkets and stores should be so damaged that a vulnerability value equal to 1 can be associated to them.

5. Vulnerability assessment

As previously introduced, the input data used for direct impact assessment are the flood inundation depths (inside the buildings), the buildings' exposure classes and the vulnerability curves. Flood inundation depths can be obtained as the result of 2D hydraulic models, considering either the discharge associated to an occurred flood event or the one calculated for a specific return period. Exposure classes can be mapped at micro-scale (i.e., single building) or at larger scales as land cover classes, but given the detail in exposure classification, the relationship between land cover class and buildings' use should be described. The last step consists in the implementation of a tool able to combine all these information and provide a vulnerability classification as result.

Although there is much literature that has discussed flood damage calculation, very few studies propose methodologies that can be applied to different case studies, and different data types and structures efficiently. Some approaches combine the land use regions and the average flood depth to evaluate the damage, but the depth-damage curves are non-linear such that the average could lead to inaccurate estimation.

In the context of the European “Collaborative Research on Flood Resilience in Urban areas” (CORFU) project, one of the objectives was to develop a framework for flood damage assessment that can be applied to different Asian and European cities. It was desirable for the tool to be (i) flexible, as the data are highly variable in different cities; (ii) developed in a framework that could be widely distributed; (iii) compatible with the spatial distribution of the majority of the data required in flood damage assessment. For these reasons, within the framework, some researchers (Chen et al. 2013; Hammond et al. 2012) from the Centre for Water Systems of the University of Exeter developed a series of tools using Python scripts and the Geoprocessing functions within the ESRI ArcGIS software environment (ESRI Inc., 2011).

The standard GIS data format have been chosen for the inputs and the outputs of the standalone executable programs so the data can be easily imported or exported in GIS software. The tools allow the minimum manual input to calculate the flood damage based on the hydraulic modelling results and other supplementary information.

By overlapping the hazard information, vulnerability for a parcel or a zoning area, and the hazard-vulnerability functions, the damage impact for unit area is then calculated.

Chapter 3 – Case study

1. Introduction

On November 2011 an exceptional thunderstorm hit the North-East part of Sicily, producing local heavy rainfall and flash flooding. The storm was concentrated on the Tyrrhenian sea coast near the town of Barcellona Pozzo di Gotto within the Longano catchment.

The rainfall was measured by a raingauge station inside the catchment, while many information on the characteristic of the consequent flood were documented during and after the event. In particular, pictures and videos of the event recorded by “common” people using new technologies allowed to derive flow velocities in some parts of the inundated area and, adding to post-event surveys, to identify accurately the perimeter of the inundated area. During these surveys it was also collected information on water depths inside the flooded area, timing of the flow, geomorphological consequences and damage estimation.

The in deep collection of data on this event made it a good case-study to which apply the proposed methodology to study the flood consequences.

In this chapter, after a description of the study area and of the November 2011 flood, are reported the results of the application of the methodology, in terms of exposure classification, hazard and vulnerability assessment.

2. Study area description

The Longano catchment is situated in the Northeast part of Sicily and drains an area of approximately 30.7 km^2, rising to around 1162 m above sea level with an average slope of 18%. On a hilltop inside the catchment rise the village of Castroreale, while in other ridges are located little hamlets like La Gala and Case Migliardo, both affected by landslides during the event of November 2011. The town of Barcellona Pozzo di Gotto, finally, is located in the valley area of the catchment (Figure 15).

Figure 15. Overview of Longano catchment area.

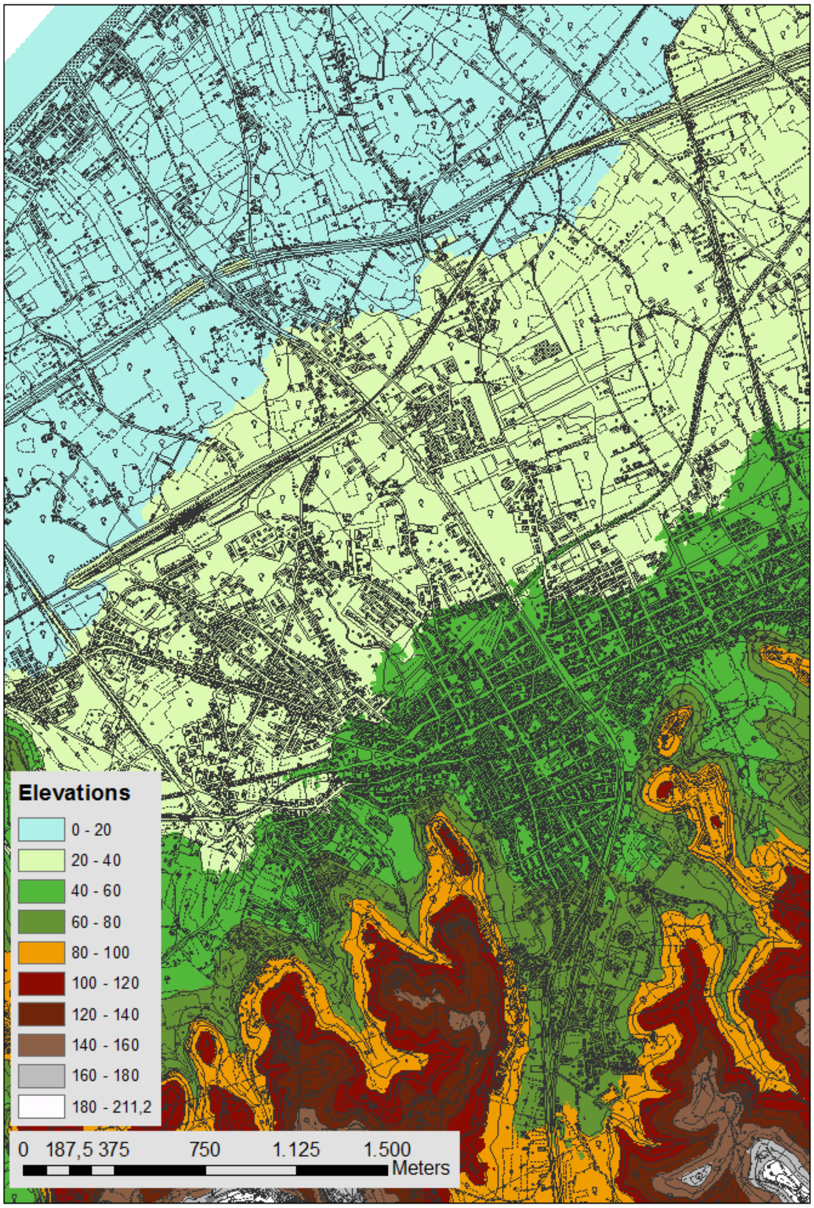

Figure 16. Survey map (1:10000) and DEM (2m resolutions) of Barcellona Pozzo di Gotto urban area.

The main branch of the Longano River is about 13.4 km in length: it is confined in a concrete rectangular channel and covered in its last part. The levees, along with the bridges and the final covering have considerably reduced its section causing frequent flood events (made worse by the presence of levees' breaches in different points). A rain gauge is located within the catchment (Castroreale), where historical rainfall data are available for the period 1930-2008.

The climate of the area is Mediterranean with a dry season from May to September and a wet season (from October to April) characterised by rainfall events with short durations and high intensities. The precipitation are strongly influenced also by the orography and by the prevalence of winds from North-West; the mountainous chain of Peloritani mounts, in fact, represents an obstacle for winds coming from Tyrrhenian and Ionian seas (Regione Sicilia, 2004). The mean annual rainfall is about 904 mm, with almost 83% in the wet season and 17% in the dry one (Figure 17).

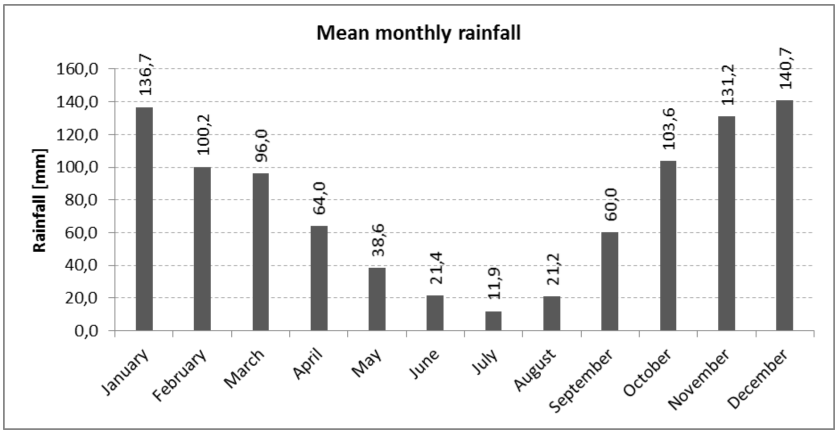

Figure 17. Mean monthly rainfall registered by Castroreale raingauge station.

3. Flood event description

The rainstorm was recorded at the rain gauge station of Castroreale: it started at 5.00 am and lasted for approximately 11 hours, with a cumulated rainfall of approximately 348 mm and two peaks of intensity of 125 and 112 mm/h (Figure 18). It caused landslides and important erosions in the upper part of the catchment, especially close to the hamlets of Castroreale and Case Migliardo (Figure 15), and a serious flood inside Barcellona Pozzo di Gotto. While some water overflowed from some breaches located upstream the city centre, the "real" flooding was caused by the overtopping of a bridge and a culvert close to the city centre. An area of almost 1 km^2 has been inundated (Figure 19) with water levels varying between 0.7 and 2 m in the central part of the city.

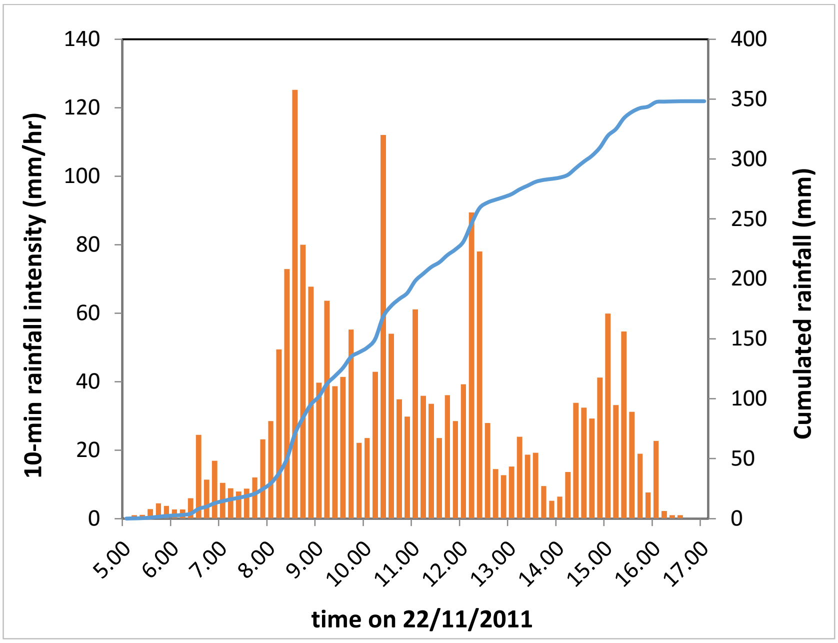

Figure 18. Rainfall intensities and cumulated rainfall registered on 22/11/2011 from Castroreale raingauge station.

The flood affected properties, buildings, roads and bridges and blocked traffic for many hours; many cars were dragged by the water and almost 800 buildings were reached from the water, one hundred of which occupied by commercial activities (Figures 20-24). Moreover, the flow caused the collapse of a bridge in the area close to the river mouth in Tyrrhenian Sea (Figure 25).

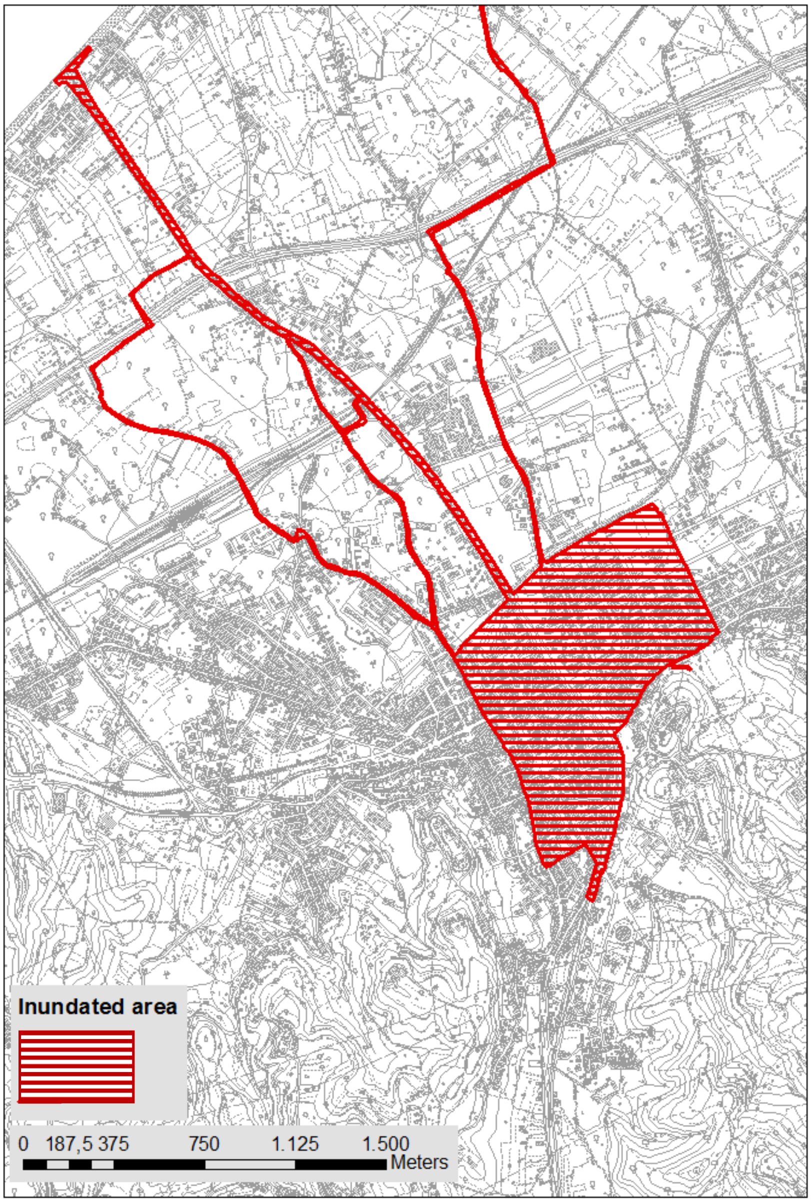

Figure 19. Layout of the inundated area.

Figure 20. Photoshoot from inundated area in Barcellona-Pozzo di Gotto city centre.

Figure 21. Photoshoot from inundated area in Barcellona-Pozzo di Gotto city centre.

Figure 22. Photoshoot of clean-up operations after the 22 November 2011 flood event.

Figure 23. Photoshoot of 22 November 2011 flood event: flooded high school with basement in Barcellona Pozzo di Gotto.

Figure 24. Photoshoot of 22 November 2011 flood event: flooded supermarket and local topographical depression.

Figure 25. Photoshoot of 22 November 2011 flood event: bridge collapsed in Barcellona Pozzo di Gotto.

4. Post-event survey (post-flood field investigation)

Field surveys were conducted in the aftermath of the event to allow for a better reconstruction of it. While peak flood timing obtained from the model were compared with data gathered from witnesses interviews, a geomorphological survey was also conducted to document erosion and sedimentation processes associated to the extreme flood ad an attempt to derive damage data was implemented and described ongoing.

Damage data collection

Some days after the event of 22th November, the municipality provided people some forms where to collect the damages occurred in their properties. Unfortunately, these forms were originally prepared for the collection of earthquakes' damages data and their feasibility in the collection of flood damage data is limited. In fact, information on the extension of flooded floors or on water depths inside the buildings lacks, such us details on damages to contents, precautionary measures implemented, estimation of costs for clean-up and recovery of pre-event conditions… In particular, the only requested information on buildings' damage are reported in Table 7, which is an extract of a form (the complete one contemplate also data regarding the owner).

Table 7. Extract of the form adopted for damage collection in the aftermath of 22 November 2011 event.

<table>
<tr><th colspan="6">BUILDING LOCATION</th></tr>
<tr><td colspan="2">STREET/SQUARE</td><td colspan="4"></td></tr>
<tr><th colspan="6">BUILDING STRUCTURE</th></tr>
<tr><td colspan="3">REINFORCED CONCRETE</td><td colspan="2">MASONRY</td><td>OTHER</td></tr>
<tr><td colspan="3"></td><td colspan="2"></td><td></td></tr>
<tr><th colspan="3">USE</th><th colspan="2">FLOOR</th><th>NOTES</th></tr>
<tr><td colspan="3">RESIDENTIAL</td><td colspan="2">BASEMENT</td><td></td></tr>
<tr><td colspan="3">COMMERCIAL</td><td colspan="2">GROUND FLOOR</td><td></td></tr>
<tr><td colspan="3">MANIFACTURAL</td><td colspan="2">MEZZANINE</td><td></td></tr>
<tr><td colspan="3">PRODUCTIVE</td><td colspan="2">FIRST FLOOR</td><td></td></tr>
<tr><td colspan="3">PROFESSIONAL</td><td colspan="2">YARD</td><td></td></tr>
<tr><td colspan="3">OTHER</td><td colspan="2">OTHER</td><td></td></tr>
<tr><th colspan="6">OBJECTS</th></tr>
<tr><td>FLOORS</td><td>PLASTER</td><td>FIXTURES</td><td>DOORS</td><td>MACHINERIES</td><td>OTHER</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><th colspan="6">NOTES</th></tr>
<tr><td colspan="6"></td></tr>
</table>

Moreover, the forms were compiled by the owners themselves, with no help from experts and no indication for a standard collection of the information: this made the compilation rough and subjective. At last, the forms resulted to be extremely synthetic. They just allowed for a first, qualitative analysis on direct tangible damages occurred during this event.

The forms collected by the municipality were 615: 577 with damages occurred to buildings, 38 with damages occurred to agricultural land. In general, no structural damages occurred to any building.

The classifications on buildings' damage possible to do were just qualitative.

The first classification concerned their use; it was distinguished among: residential use, commercial use, industrial-productive use, other uses. The forms did not allow for any distinction among commercial activities, and this aspect hampers any possibility to deduce damage occurred to machineries or stocks. However, it could be plausible to attribute to the buildings inside the ensemble “other uses” the function of warehouse.

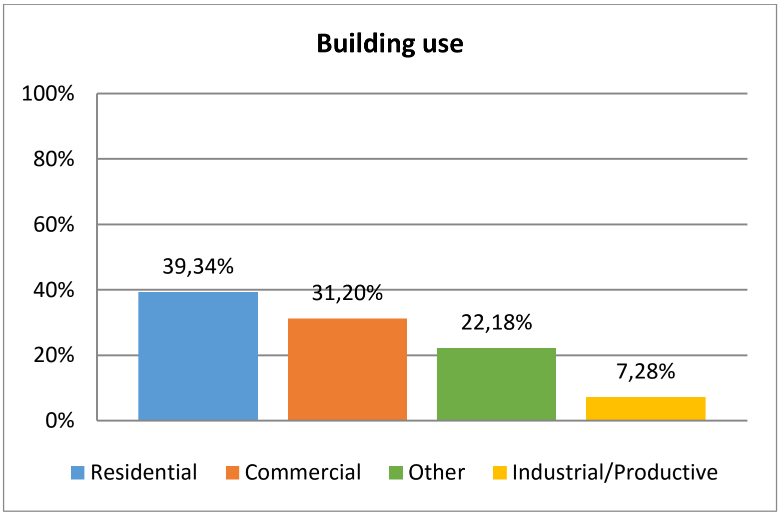

Figure 26. Classification of the collected damage data according to the use destination of the affected buildings.

The second classification concerned the localization of the damage inside the building, distinguishing among basement, ground floor, mezzanine, first floor, yard, others. In this case, it was hypothesized that people, selecting “other”, intended private garden.

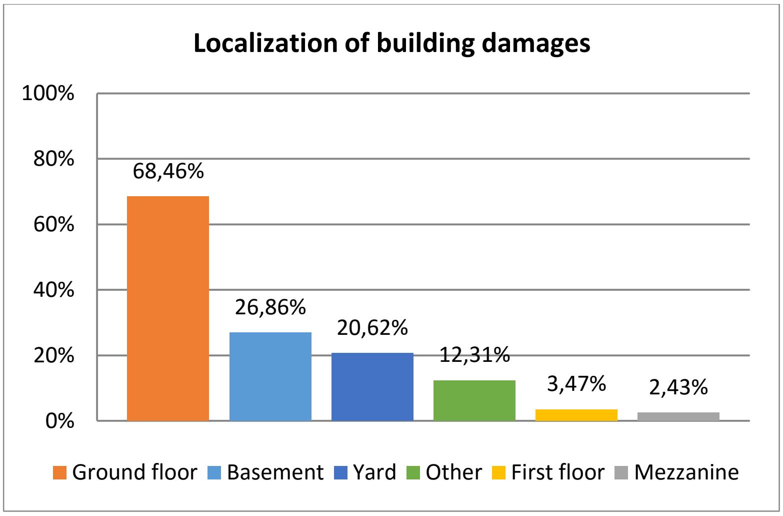

Figure 27. Classification of the collected damage data according to the localization of the damage inside the building.

The last classification regarded the elements damaged, distinguishing among floors, walls, doors, windows, machineries (for productive buildings), household appliances (for residential buildings), others. In this case, instead, it was impossible to attribute to the class "others" a specific meaning, as it could contemplate a too wide range of objects.

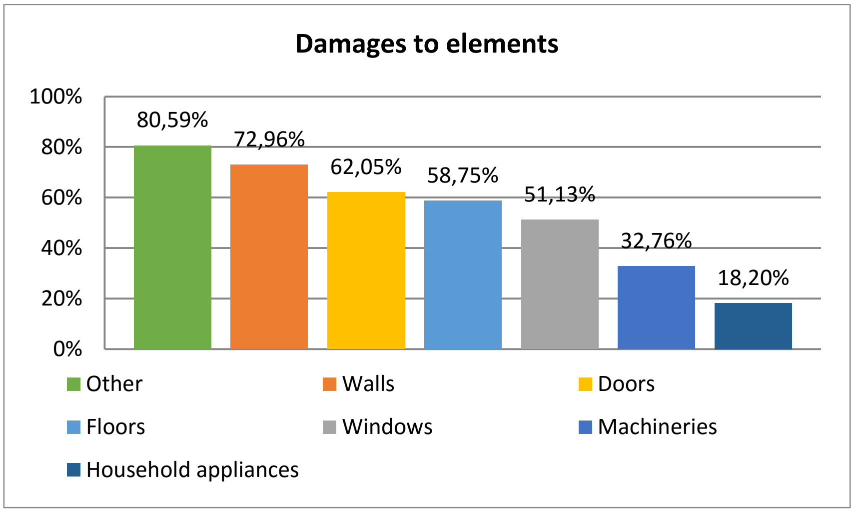

Figure 28. Classification of the collected damage data according to the damaged element inside the building.

5. Modelling

5.1 Rainfall-Runoff transformation model

To simulate the rainfall-runoff process, because of the high spatial variability of weather phenomena in Mediterranean areas, a conceptual fully distributed model with climatic dependencies was used (Candela et al, 2015).

The model used is based on the representation in the form of linear kinematic mechanism of transfer of the full outflows coming from different contributing areas of the basin through the definition of a distributed hydrological response array with climatic characteristics.

Rainfall inputs are, also, distributed in space and time-varying. They are represented using a three-dimensional matrix, *P*, of order (*A*, *B*, *N*) where *A* and *B* are the number of cells in which the basin is divided in the direction *x* and *y*. *N* represents intervals number in which the rainfall event of duration Ω (with $N = \Omega/\Delta t$) is divided for each cell:

$$P_{(A,B,N)} = \begin{bmatrix} P_{1,1,N} & P_{1,2,N} & \cdots & P_{1,B,N} \\ & & P_{i,j,t} & \\ \vdots & & & \vdots \\ P_{A,1,N} & P_{A,2,N} & \cdots & P_{A,B,N} \end{bmatrix} \tag{4}$$

in which the generic term $P_{i,j}$, t represents rainfall, expressed in mm, falling on the cell of coordinates *i*, *j* at time *t*.

The SCS-CN method, adopted by USDA Soil Conservation Service (1972, 1986), is used to transform the gross rainfall in effective rainfall. This method allows incorporating information on land use change as the CN is a function of soil type, land use, soil cover condition and degree of saturation of the soil before the start of the storm.

Since, a precipitation variable in time is considered, the runoff volume, $P_{e,i,j,t}$, is calculated in a dynamic form (Chow et al, 1988) as a function of the storm depth $P_{i,j,t}$, given initial abstraction, $I_{a,i,j} = cS_{i,j}$, in turn a function of the potential maximum soil moisture retention after runoff begins *S* according to the coefficient c, and the infiltrated volume, $F_{i,j,t}$, also variable over time, according to the following expression:

$$P_{e,i,j,t} = \begin{cases} 0 & P_{i,j,t} < c \cdot S_{i,j} \\ P_{i,j,t} - c \cdot S_{i,j} - F_{i,j,t} & P_{i,j,t} > c \cdot S_{i,j} \end{cases} \tag{5}$$

with $F_{i,j,t}$ calculated with the following expression:

$$F_{i,j,t} = \frac{S_{i,j} \cdot \left(P_{i,j,t} - c \cdot S_{a,i,j}\right)}{P_{i,j,t} - c \cdot S_{a,i,j} + S_{i,j}} \tag{6}$$

and:

$$S_{i,j} = 254 \cdot \left(\frac{100}{CN_{i,j}} - 1 \right) \tag{7}$$

The $CN_{i,j}$ parameter is, also, defined in a distributed form starting from a map of its spatial distribution obtained on the basis of the knowledge of soil types, land use and hydrologic soil types. The matrix *H*, which describes the hydrological response of the basin, represents the space-time distribution of contributing areas (isochrones areas). It can be derived starting from concentration time and location of each cell within the catchment. Particularly, Wooding formula (1965) has been used to derive concentration time at cell scale:

$$\vartheta_{i,j} = \frac{L_{i,j\to out}^{3/5}}{k_{i,j\to out}^{3/5} \cdot s_{i,j\to out}^{3/10} \cdot r_{i,j}^{2/5}} \tag{8}$$

where $L_{i,j\to out}$ [m] is the hydraulic path length between the centroid of the cell of coordinates *i,j* and the outlet section of the catchment, $k_{i,j\to out}$ [$m^{1/3}/s$] is the Strickler roughness for the same path, $s_{i,j\to out}$ [m/m] is its slope, and $r_{i,j}$ [m/s] is the average rainfall intensity for the rainfall event over the cell of coordinates *i,j*.

H matrix is of order (Θ,*A*,*B*) where Θ is the number of intervals in which catchment concentration time ϑ_{catch} is discretised:

$$H_{(\Theta,A,B)} = \begin{bmatrix} H_{1,1,1} & H_{1,1,2} & \cdots & H_{1,1,B} \\ & & H_{n,i,j} & \\ \vdots & & & \vdots \\ H_{\Theta,A,1} & H_{\Theta,A,2} & \cdots & H_{\Theta,A,B} \end{bmatrix} \tag{9}$$

where $H_{\Theta,i,j}$ represents the cell surface of *i,j*-coordinates and a concentration time ϑ_n (with $\vartheta_n = \vartheta_{catch}/n\cdot\Delta t$, and $n = 1,2, ..,\Theta$).

The matrix of runoff *Q* is obtained by multiplying hydrological response matrix, *H* with the effective rainfall matrix, P_e :

$$Q_{(\Theta,N)} = H_{(\Theta,A,B)} \times P_{e(A,B,N)} = \frac{1}{\Delta t}\cdot \begin{bmatrix} Q_{1,1} & Q_{1,2} & \cdots & Q_{1,N} \\ & & Q_{i,j} & \\ \vdots & & & \vdots \\ Q_{\Theta,1} & Q_{\Theta,2} & \cdots & Q_{\Theta,N} \end{bmatrix} \tag{10}$$

in which $Q_{i,j}$ represents the available runoff for the ϑ isochrone zone at time *t*.

The paths lengths and their average slopes have been extracted from the catchment DEM available for this study with a resolution of 2 m.

The spatially-averaged value of $CN_{i,j}$ can be easily calculated starting from its effective spatial distribution, which is available for the entire Sicily at 100 m grid resolution, by using standard GIS tools. Its value is equal to 82 for AMC condition II.

The spatially-averaged value of $k_{i,j\rightarrow out}$ can be easily calculated starting from its effective spatial distribution of CN, in relation of soil type and land use by the modified Engmann's table (Engmann, 1986; Candela et al., 2005) (Table 8), by using standard GIS tools. Its value was set equal to 20.5 $m^{-1/3}$/s.

Table 8. Engmann modified table reported Strickler's coefficient values related to Longano catchment land use.

Land use	Urban	Bare rocks	Arable land	Untilled	Vineyard	Clear forest
Strickler coefficient	100.0	50.0	22.0	20.0	7.69	6.67

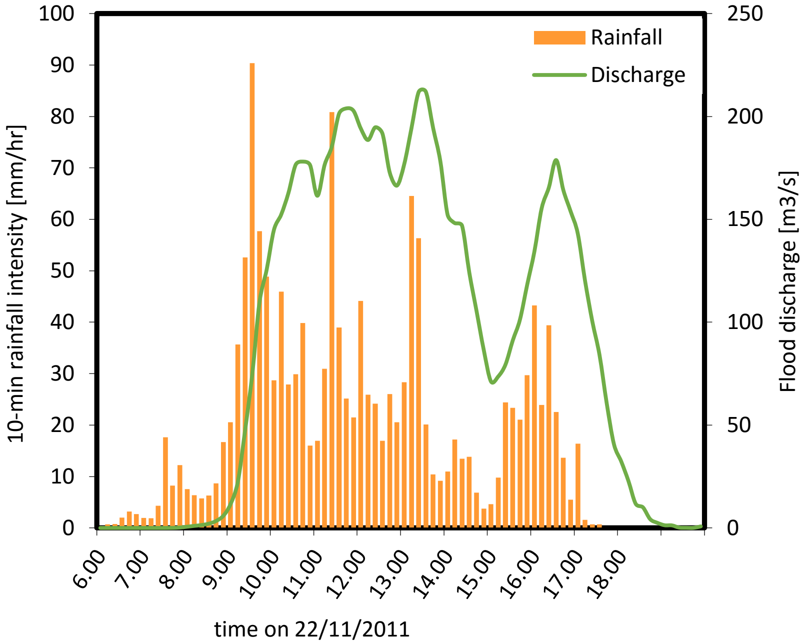

Figure 29. Rainfall intensities and flood hydrograph derived from the R-R modelling.

5.2 Hydraulic model and calibration

A description of the MLFP-2D model by Aronica et al. (1998) used for flow propagation was reported in chapter 2, section 2.3. Here the details of the finite element mesh (Figure 31), the initial and the boundary conditions, and the model calibration.

The definition of the finite element mesh boundary (Figure 30) was based on the morphology of the study area in order to cover alluvial fan, to leave the blocks and the single houses out of the domain and to take in account internal barriers and hydraulic discontinuities.

The total domain area is about 1.74 km^2 and was discretized in 53081 triangular elements. The geometric features (x,y,z coordinates) of 31814 nodes have been derived from the Digital Elevation Map (DEM) with 2m resolution.

The wide area modelled outside the river (and beyond the observed inundated area) ensures the non-interaction with the flow, as the domain contour represents for the model an impermeable boundary.

The flow hydrograph derived with the R-R distributed model was considered as boundary condition in the upstream river nodes.

In the MLFP-2D, the Strickler roughness coefficient is the unique parameter involved, which is spatially distributed. The model structure allows one coefficient for each triangular element to be used, but based on land use, the domain was divided into two principal regions: river channel and floodplain.

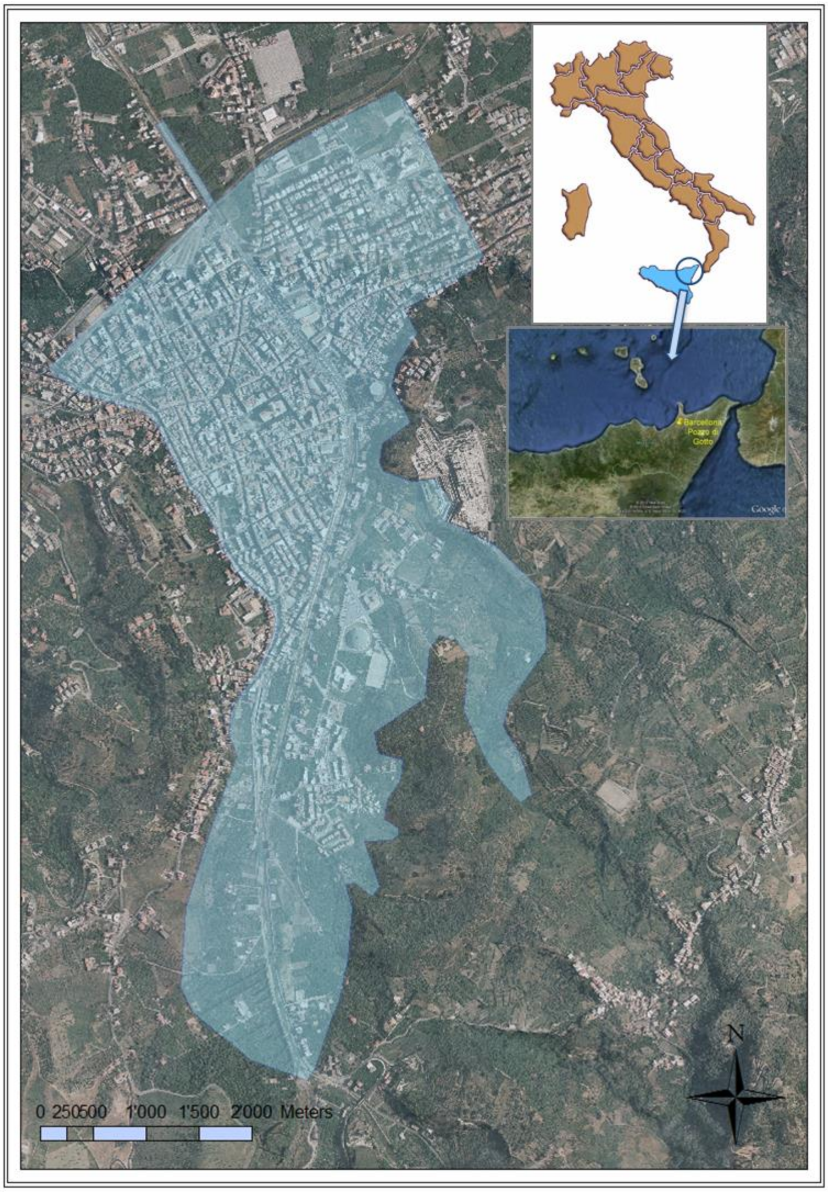

Figure 30. Layout of the modelled area.

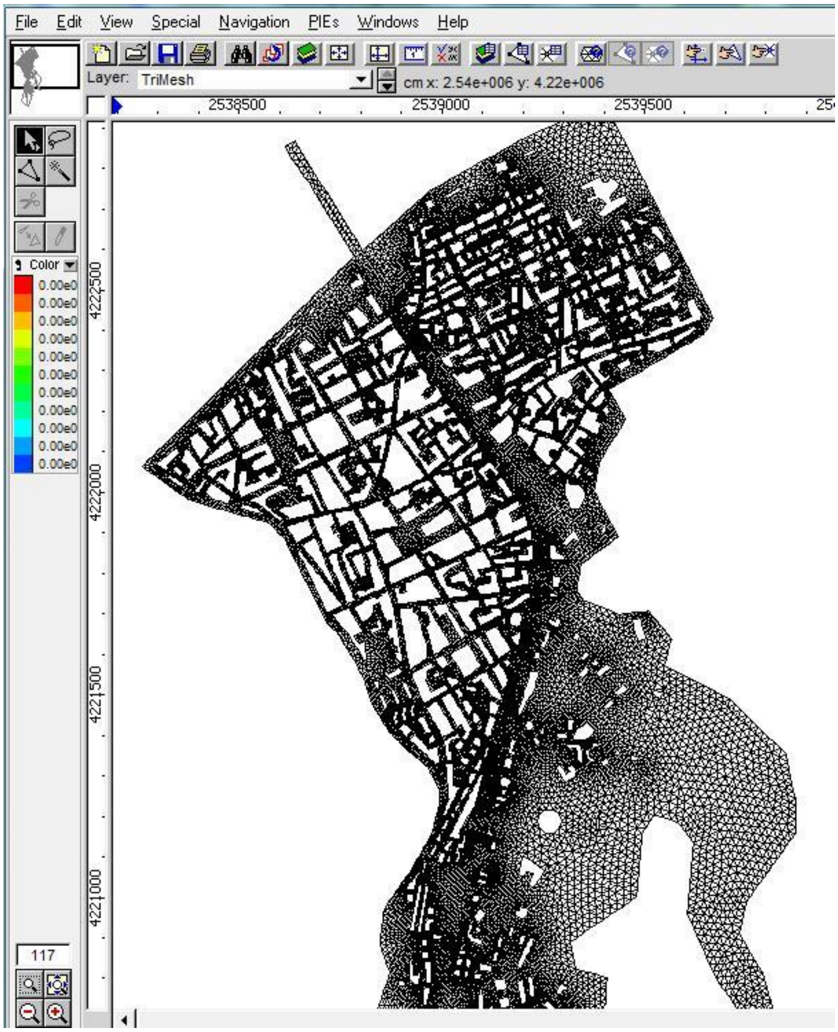

Figure 31. Detail of the finite element mesh.

As introduced in chapter 2 (section 2.4), in order to minimize computational errors, the model has been previously calibrated with reference to floodplain and river channel roughness (assumed the most important parameter controlling the inundation extent). The calibration was performed through Monte Carlo simulations using both the measured inundation depths and the flow velocities deduced from event's movie frames analysis.

The first step of the procedure is to decide the range of the feasible parameter space to be examined. This first decision, significantly, can influence predicted uncertainties. Following previous study (Aronica et al., 1998b, Aronica et al 2002), friction values, in terms of Manning's *n* for the calibration process, were randomly and uniformly distributed between 0.035 $m^{1/3}s^{-1}$ and 0.1 $m^{1/3}s^{-1}$ for the river, and 0.045 $m^{1/3}s^{-1}$ and 0.2 $m^{1/3}s^{-1}$ for the floodplain.

The recorder water depths (WD) and flow velocities (VEL) are compared to the simulated to calculate the residuals. The errors between the observed and predicted outputs, the residuals, are formulated as:

$$(\varepsilon_i)_{WD} = (h_{i,obs} - h_{i,sim}(\theta)) \quad i = 1,\ldots,m \tag{11a}$$

$$(\varepsilon_i)_{VEL} = (v_{j,obs} - v_{j,sim}(\theta)) \quad j = 1,\ldots,n \tag{11b}$$

where *m*= number of observations for inundation water dephts; *n*= number of observations for flow velocities; θ= vector of model parameters (i.e. roughness coefficients); $h_{i,obs}$= observed water depth at *i*-th site; $h_{i,sim}(\theta)$= simulate water depth at the same site generated using the parameter values θ; $v_{j,obs}$= observed flow velocity at *j*-th site; $v_{j,sim}(\theta)$= simulate flow velocity at the same site generated using the parameter values θ.

Particularly, the Monte Carlo procedure was implemented through multiple model simulations by mapping the parameter space to the continuous space of two performance measures or objective functions: Residual Sum of Squares (SSR) and the Root Mean Square Error (RMSE) of the simulation results from the measures inundation depths (WD) and, both, measures inundation depths (WD) and flow velocities (VEL) calculated as follows:

$$SSR = \sum_{i=1}^{m} (\varepsilon_i)_{WD}^{2} \tag{12a}$$

$$SSR = w_{WD}\left[\sum_{i=1}^{m} (\varepsilon_i)_{WD}^{2}\right] + w_{VEL}\left[\sum_{j=1}^{n} (\varepsilon_j)_{VEL}^{2}\right] \tag{12b}$$

$$RMSE = \sqrt{\frac{i}{m}\sum_{i=1}^{m}\left(\varepsilon_i\right)_{WD}^{2}} \tag{13a}$$

$$RMSE = w_{WD}\left[\sqrt{\frac{i}{m}\sum_{i=1}^{m}\left(\varepsilon_i\right)_{WD}^{2}}\right] + w_{VEL}\left[\sqrt{\frac{i}{n}\sum_{j=1}^{n}\left(\varepsilon_j\right)_{VEL}^{2}}\right] \tag{13b}$$

where w_{WD} and w_{VEL} are weights that are assigned to the type of observations. The weights in the objective function allow to focus on a type of observation rather the other, in this study a value equal to 0.5 has been assigned to both weights; θ is the vector of model parameters (roughness coefficients); $h_{i,obs}$ is observed water depth at *i*-th site; $h_{i,sim}(\theta)$ is simulate water depth at the same site generated using the parameter values θ.

6. Results

6.1 Hazard classification

The variable selected to describe flood hazard is the water depth, as it is the only one whose influence on vulnerability is considered in the vulnerability curves.

In particular, it has been mapped (as output of the 2D model) the envelope of the maximum water depths occurred during the simulation. As expected, the most affected areas are those in correspondence of the bridges overtopping.

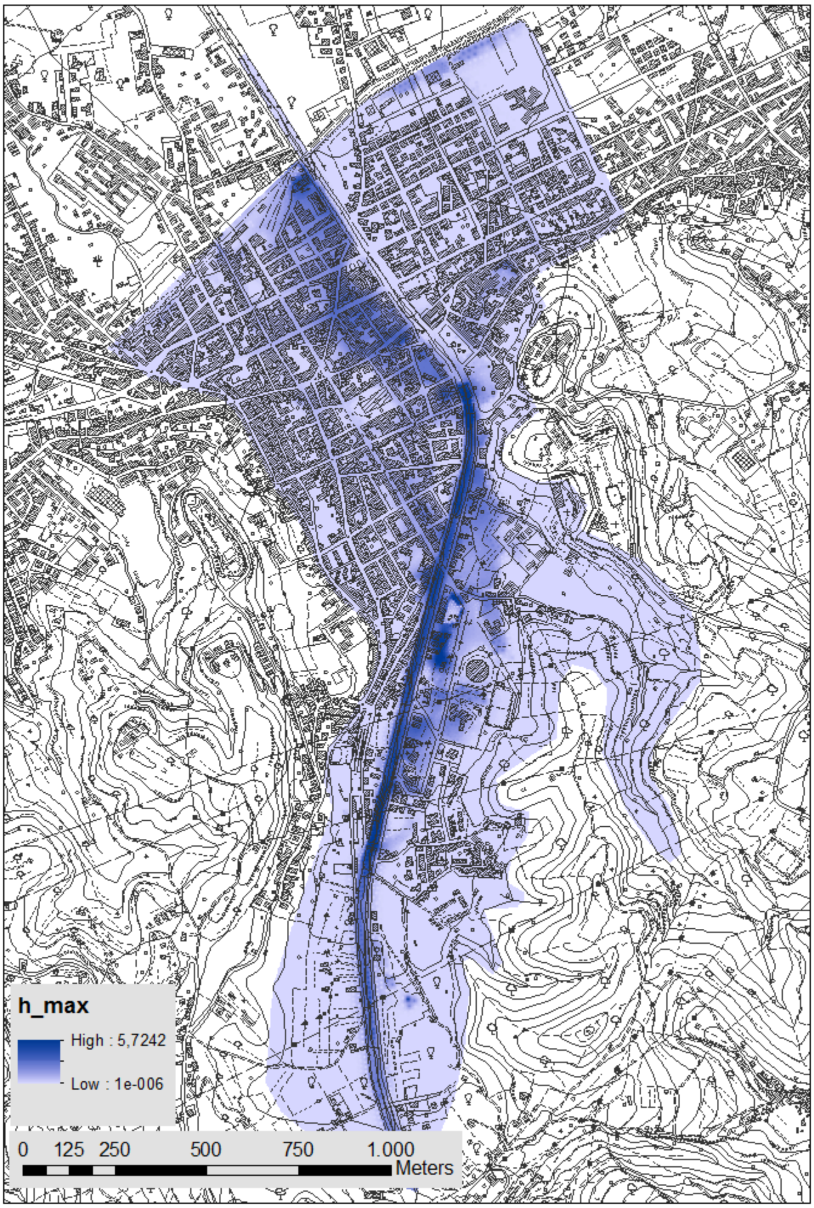

Figure 32. Flood depth resulting from the 2-D hydraulic modelling.

On a GIS Platform, the inundation depths inside the buildings have been derived as the mean inundation depth value along their contours (Figure 33).

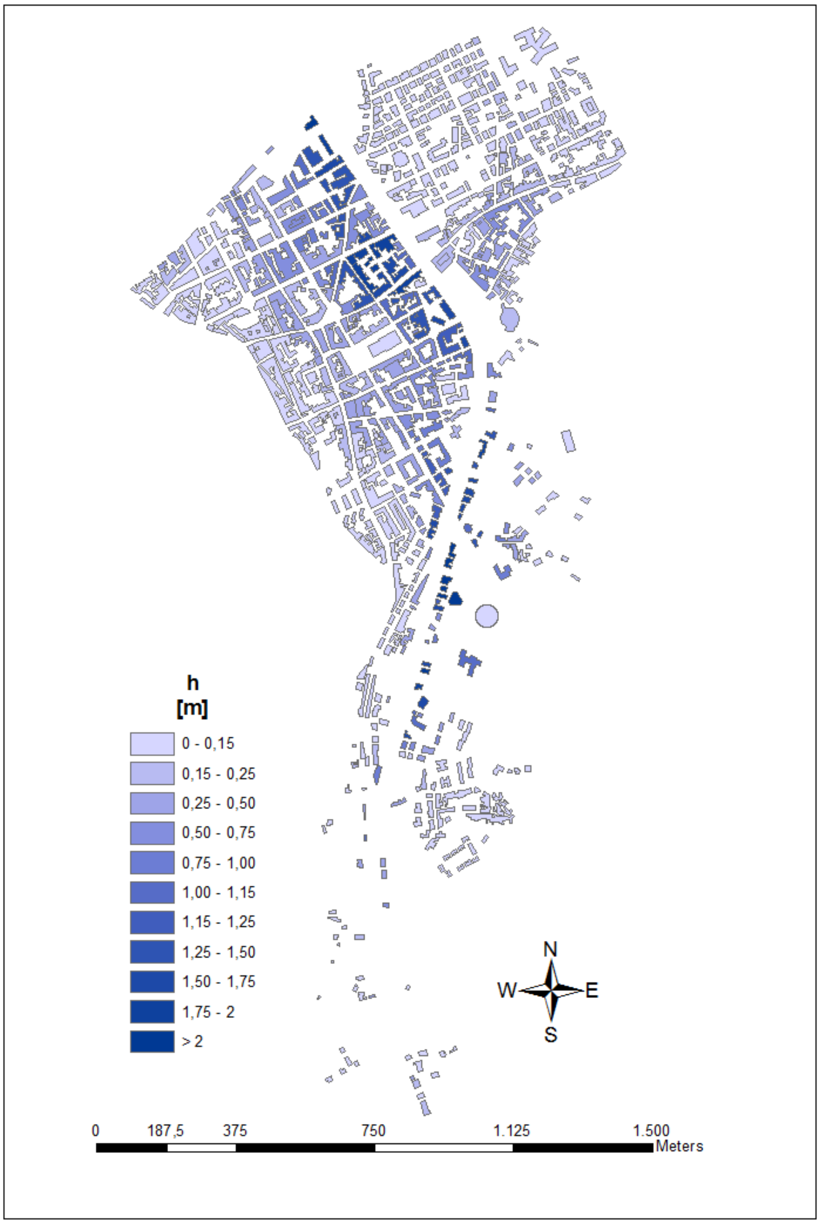

Figure 33. Flood depths inside buildings' contour.

6.2 Exposure classification

The description of the methodology used to derive the exposure classification, starting from the Sicilian Flood Risk Plan (Regione Sicilia, 2004), are described in chapter 2, section 3.

Thanks to field surveys and Google Street, the Exposure classification was carried out at the micro-scale for buildings in the study area and results have been reported in raster format (Figure 34).

In case of mixed-use (residential and commercial) buildings, the classification referred to ground floor class (the water depths occurred in past flood events, in fact, has not been so high to reach the raised floors).

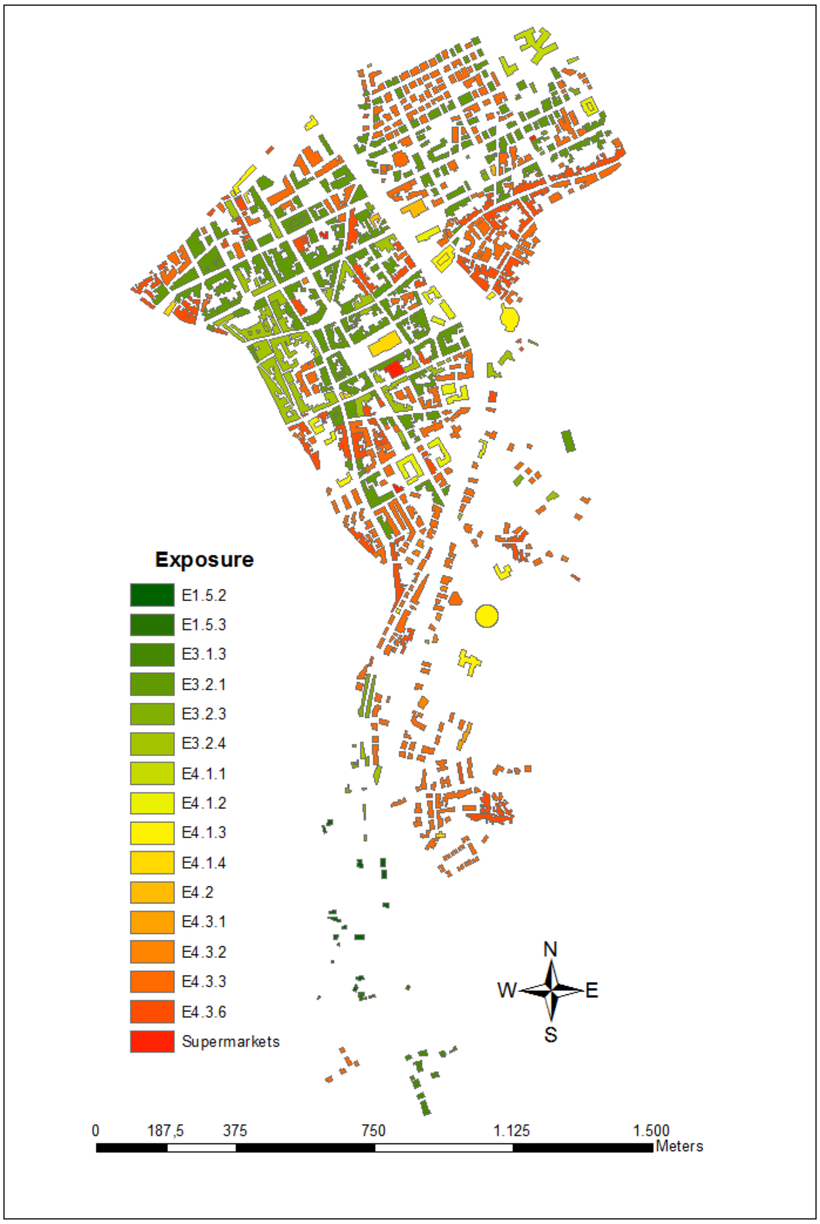

Figure 34. Exposure map.

In Figure 35, instead, the classification of commercial and residential buildings in function of their finishes classes.

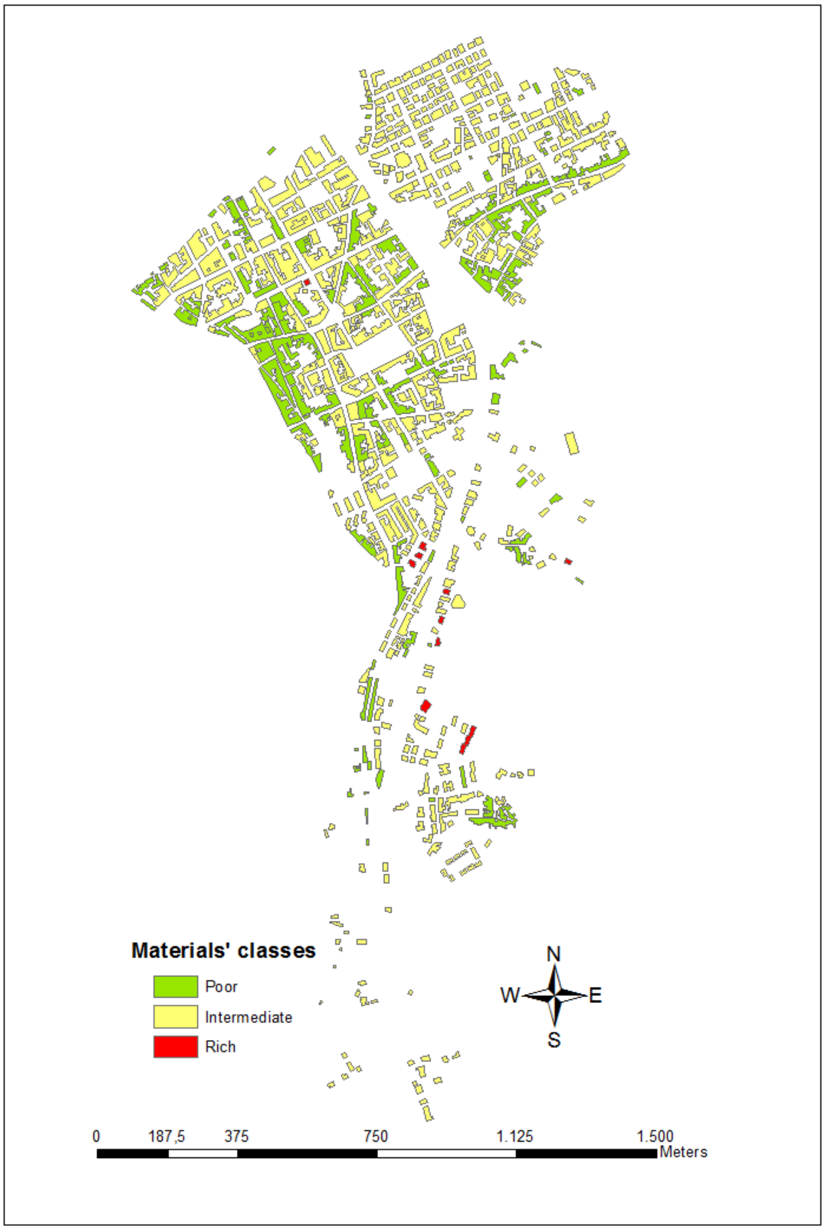

Figure 35. Buildings' classification according to their finishes.

6.3 Vulnerability curves

In section xx has been introduced and described the synthetic approach followed for the derivation of vulnerability curves for the Sicilian territory.

Through a questionnaire, a team of experts was consulted for describing the proportional damage suffered by buildings' elements (floors, walls, doors, windows, French windows, wiring, hydraulics, gas systems, water systems, bathroom fixtures) with growing water depths.

The questions developed were intentionally open and generic, in order to allow each expert to describe any result from his personal field experiences. It was asked them to refer to a reinforced concrete building subjected to a water flooding without suffering any structural damage due to the flooding event.

Almost every expert made a consideration regarding the (simple?) water hypothesis: in fact, they all have experienced floods where sediments' presence was conspicuous (evident) and influenced direct damages, especially the ones to furniture. Another consideration regarded the hypothesis to neglect damages to goods because, conversely to building elements, they suffer damage after almost all events. This hypothesis was kept because of the impossibility to validate the results because of the total lack of correspondent data. Moreover, in the optic of a general moving to the adoption of insurance policies for natural hazards, that will not cover damage to contents, or will consider them as a percentage of damage to structures, the derivation of relative damage curves for buildings' contents would be premature and maybe not useful.

Because many interviewed agreed in underlying the influence on damage of flood duration and of finishes' materials (e.g., difference between permeable or gypsum plaster, or between wooden or aluminium windows, or between floors laid on mortar or concrete, etc.), these aspects were considered. In fact, as descripted in section xx, short and long duration (more than 36 hours) event were distinguished and poor, intermediate and rich materials too.

Examples of the intermediation among curves provided by experts for the floors is reported in Figures 36 and 37 (in red, the interpolation curve):

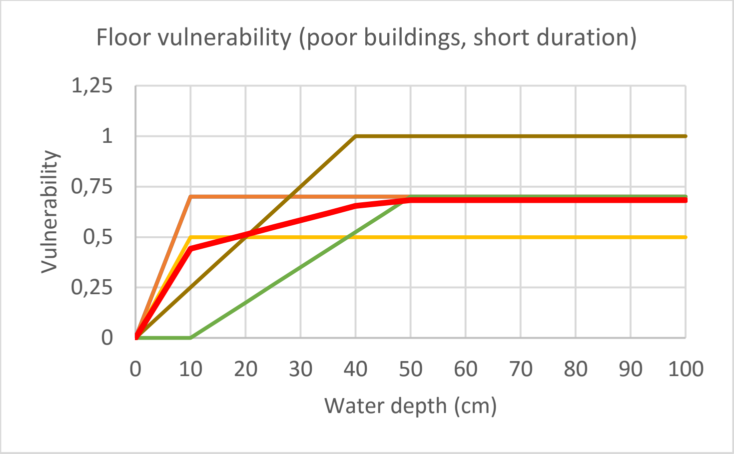

Figure 36. Vulnerability curves relative to floors according to the experts' opinion (for short duration events).

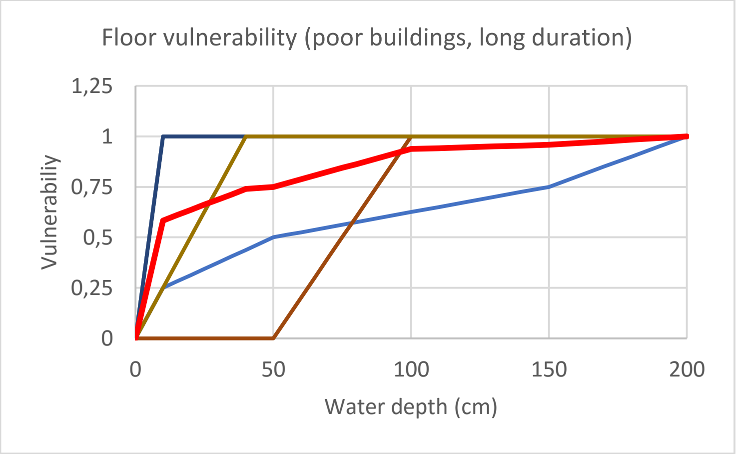

Figure 37. Vulnerability curves relative to floors according to the experts' opinion (for long duration events).

Other hypothesis regard the position of the elements from the floor: the window height considered is 90 cm; the electrical outlets are placed 30 cm from the floor, while switches and other outlets are placed 110 cm from the floor; the gas stopcock for the cookers are placed 60 cm and the one for the boiler 140.

It was said that to derive the total vulnerability it was than assigned to each element a weight in function of its substitution cost respect to the total substitution costs. Using the official price list for Sicily, the calculations referred to a standard room (20 square meters) with a door, a window, a French window, 5 electrical outlets (height 30 cm), 2 switches and other 3 electrical outlets (height 110 cm). Standard weights of 0,1 were assigned to the gas and the water systems, because there can be too many configuration their elements may assume and it would need a proper what-if analysis with field data to decide a plausible one.

While considering growing water depths, the weights of some elements necessarily change. The walls, for example, need to be completely repainted independently from the water depth reached within the room, but the quantity of plaster which must be scraped, led to landfill and substituted depends on the water depth. The windows too have a weight equal to 0 until the water depth is less than 90 cm. The same for the wiring: it assumes different weights before and after that the water has reached the height of 110 cm.

Table 9. Derivation of buildings' elements' weights for buildings "poorly finished".

		Poor buildings' finitures						
		Floors	Walls	Doors	Windows	Wiring	Gas system	Water system
h = 50 cm	Substitution costs [€]	1884,24	674,29	1669,36	0,00	282,40	-	-
	TOTAL	4510,29						
	Weights	**0,33**	**0,12**	**0,30**	**0,00**	**0,05**	**0,1**	**0,1**
h = 100 cm	Substitution costs [€]	1884,24	1024,76	1669,36	0,00	282,40	-	-
	TOTAL	4860,76						
	Weights	**0,31**	**0,17**	**0,27**	**0,00**	**0,05**	**0,1**	**0,1**
h = 150 cm	Substitution costs [€]	1884,24	1375,23	1669,36	593,71	367,20	-	-
	TOTAL	5889,73						
	Weights	**0,26**	**0,19**	**0,23**	**0,08**	**0,05**	**0,1**	**0,1**

Table 10. Derivation of buildings' elements' weights for "intermediate" buildings.

		Intermediate buildings' finitures						
		Floors	Walls	Doors	Windows	Wiring	Gas system	Water system
h = 50 cm	Substitution costs [€]	2122,24	770,41	1785,16	0,00	282,40	-	-
	TOTAL	4960,21						
	Weights	**0,34**	**0,12**	**0,29**	**0,00**	**0,05**	**0,1**	**0,1**
h = 100 cm	Substitution costs [€]	2122,24	1195,58	1785,16	0,00	282,40	-	-
	TOTAL	5385,38						
	Weights	**0,32**	**0,18**	**0,27**	**0,00**	**0,04**	**0,1**	**0,1**
h = 150 cm	Substitution costs [€]	2122,24	1620,75	1785,16	648,91	367,20	-	-
	TOTAL	6544,25						
	Weights	**0,26**	**0,20**	**0,22**	**0,08**	**0,04**	**0,1**	**0,1**

Table 11. Derivation of buildings' elements' weights for buildings "richly finished".

		Rich buildings' finitures						
		Floors	Walls	Doors	Windows	Wiring	Gas system	Water system
h = 50 cm	Substitution costs [€]	2747,64	916,75	2716,42	0,00	282,40	-	-
	TOTAL	6663,21						
	Weights	**0,33**	**0,11**	**0,33**	**0,00**	**0,03**	**0,1**	**0,1**
h = 100 cm	Substitution costs [€]	2747,64	1357,22	2716,42	0,00	282,40	-	-
	TOTAL	7103,68						
	Weights	**0,31**	**0,15**	**0,31**	**0,00**	**0,03**	**0,1**	**0,1**
h = 150 cm	Substitution costs [€]	2747,64	1797,69	2716,42	767,46	367,20	-	-
	TOTAL	8396,40						
	Weights	**0,26**	**0,17**	**0,26**	**0,07**	**0,03**	**0,1**	**0,1**

Once derived the different weights (for water depth less than or equal to 50 cm, between 50 e 100 cm, between 100 e 150 cm, greater than 150 cm) and, consequently, the different branches of the curves, we put them together in two curves distinguishing between short and long flood duration.

In Figures 38-43 are reported the vulnerability curves for the different materials and flood durations.

Under the curves, different colours have been used to distinguish the contributions of the different elements to the total vulnerability. As expected from previous considerations, floors contribution decreases with growing water depths, while windows contribution starts for water depths higher than 90 cm.

In correspondence of the gas stopcocks and the electrical outlets, there should be jumps in the curve: this typology of graph does not allow visualizing them, but they can be seen in the graphs with the curves’ comparisons (Figures 44-46).

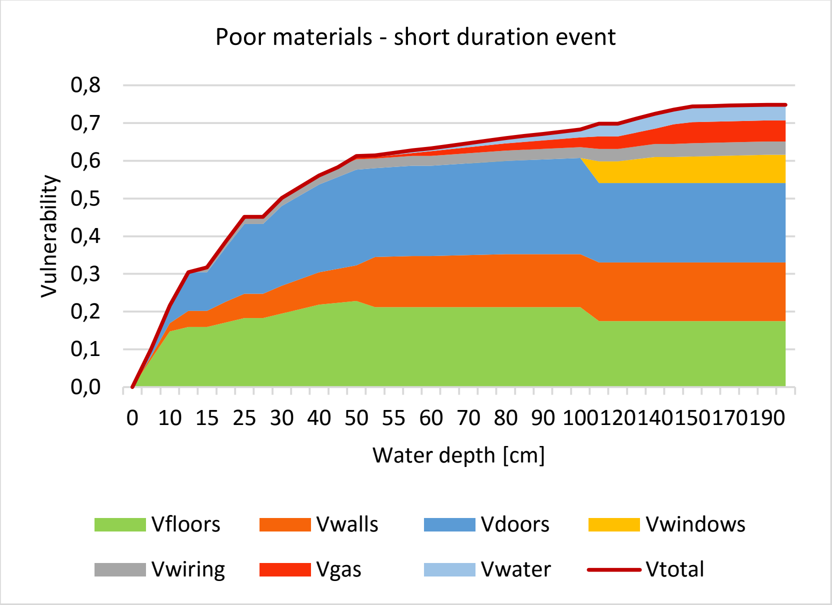

Figure 38. Vulnerability curve for buildings "poorly finished" and short duration event, with buildings' elements' contributions.

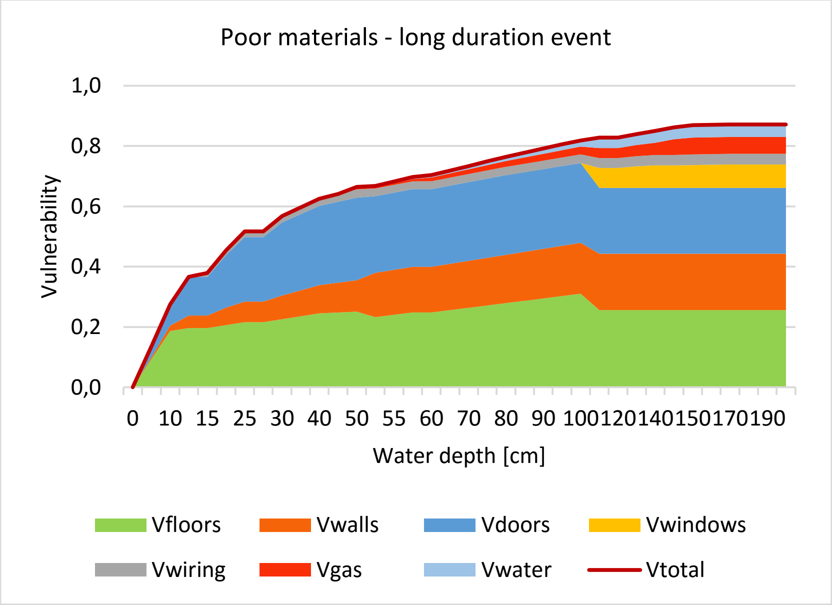

Figure 39. Vulnerability curve for buildings "poorly finished" and long duration event, with buildings' elements' contributions.

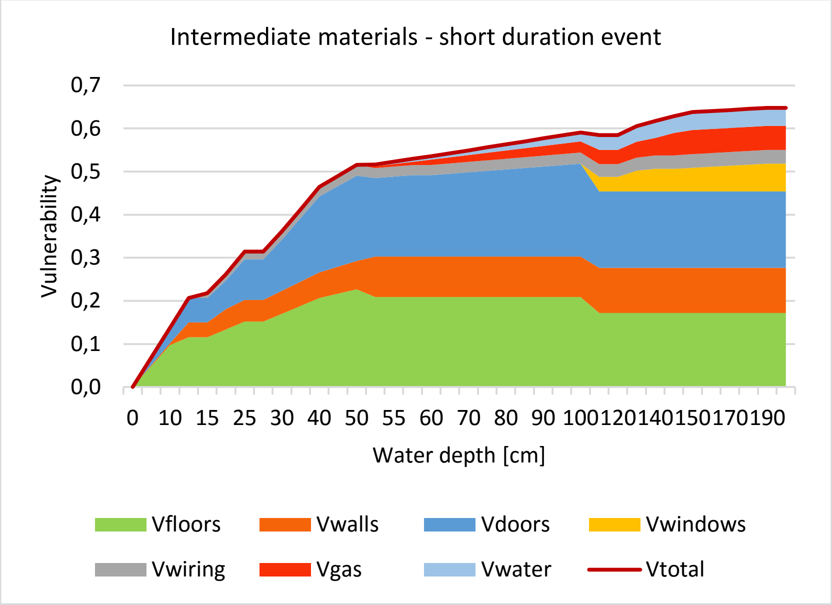

Figure 40. Vulnerability curve for “intermediate” buildings and short duration event, with buildings’ elements’ contributions.

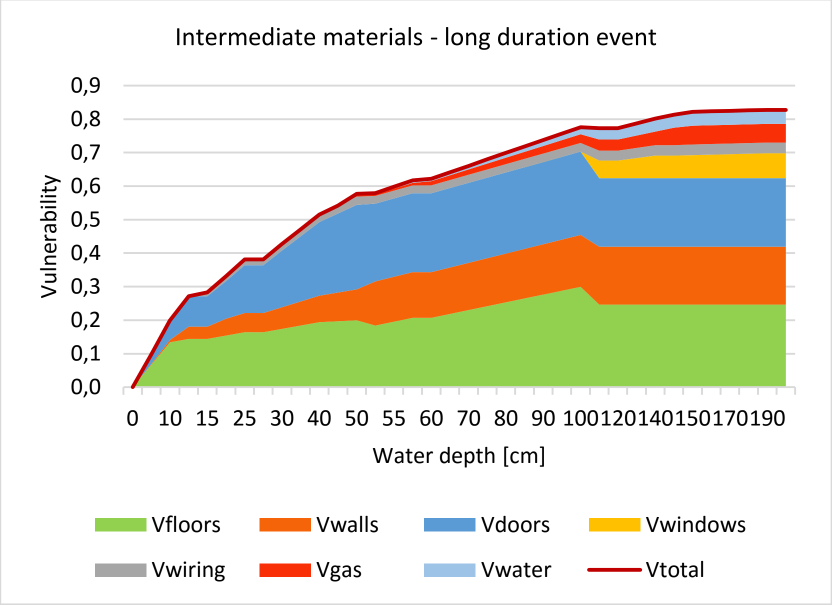

Figure 41. Vulnerability curve for “intermediate” buildings and long duration event, with buildings’ elements’ contributions.

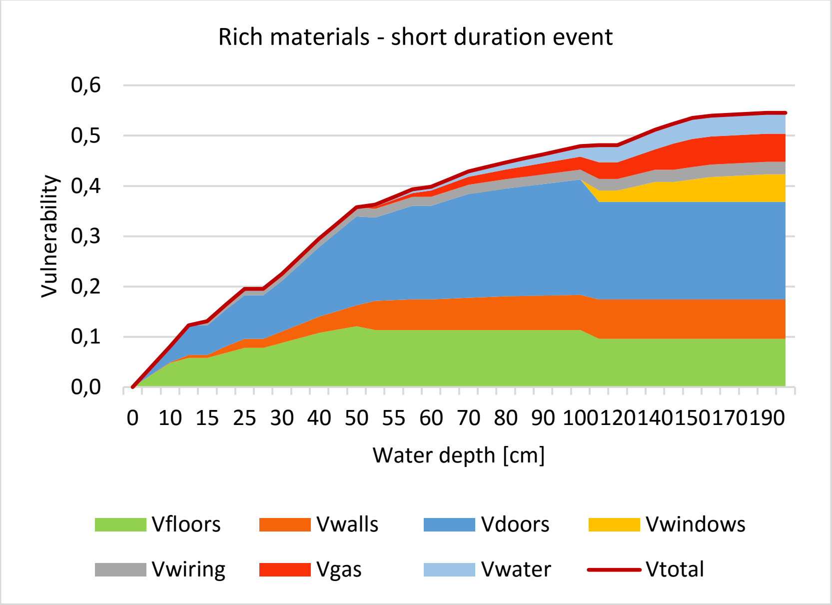

Figure 42. Vulnerability curve for buildings "richly finished" and short duration event, with buildings' elements' contributions.

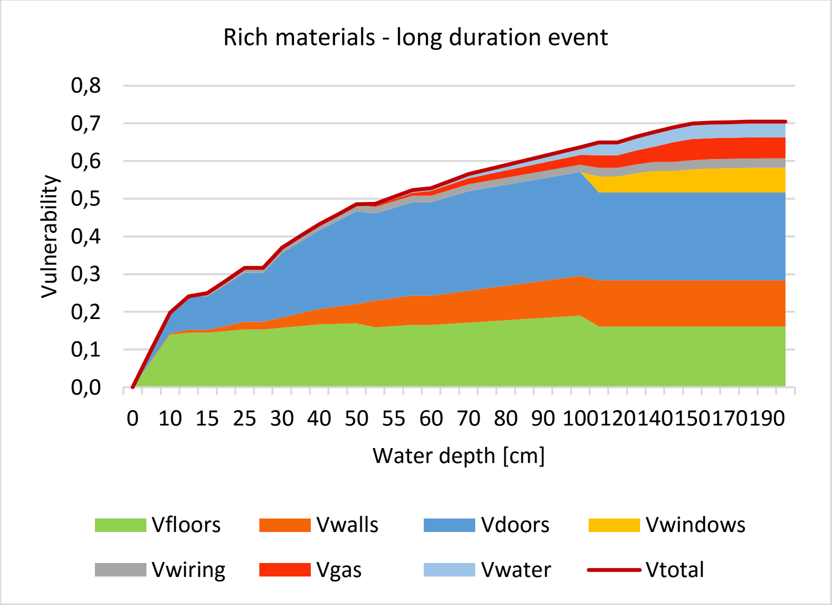

Figure 43. Vulnerability curve for buildings "richly finished" and long duration event, with buildings' elements' contributions.

In the passage between short and long duration events, the entity of flood damages of course increase.

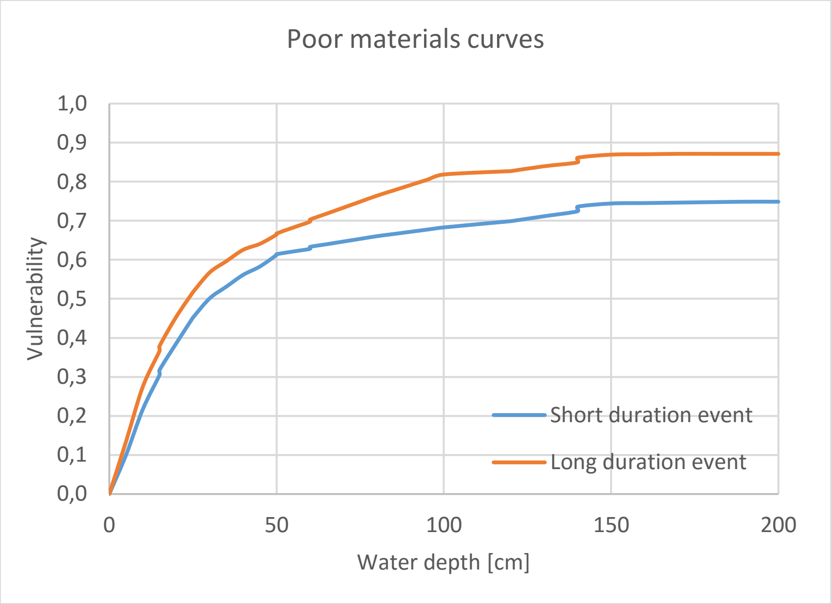

Figure 44. Comparison between short and long duration event curves for "poorly finished" buildings.

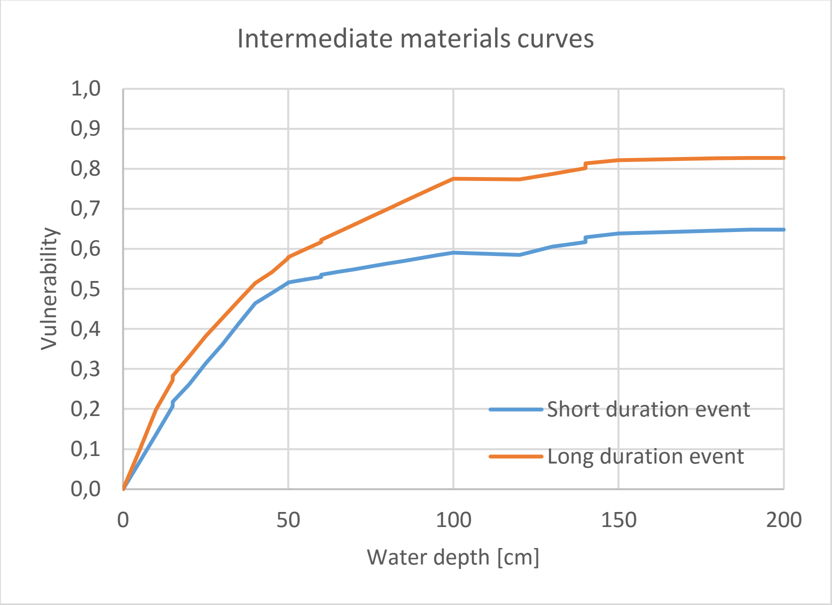

Figure 45. Comparison between short and long duration event curves for "intermediate" buildings.

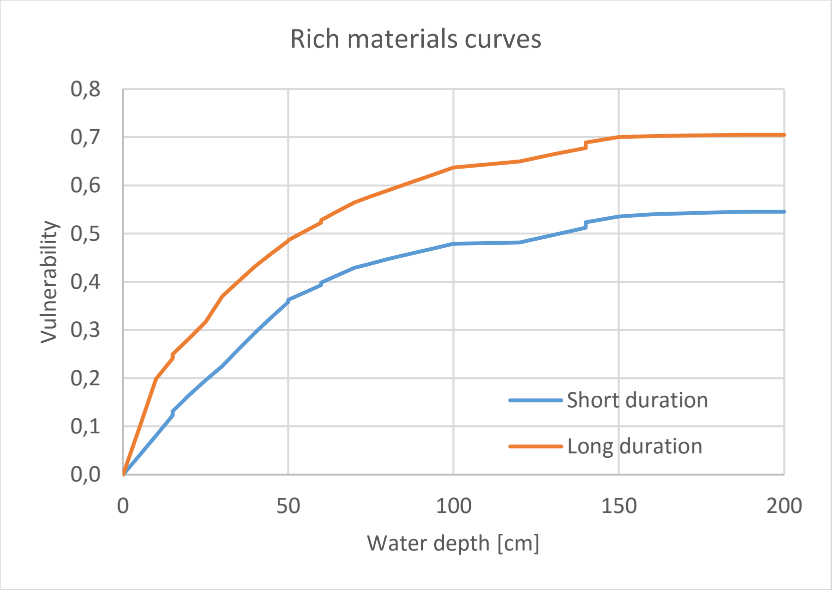

Figure 46. Comparison between short and long duration event curves for "richly finished" buildings.

A consideration is needed regarding the highest value of the total vulnerability that, as can be seen in the figure, is almost equal to 0,7. In fact, when the curves associated to each single element were derived, as a synthesis of the questionnaire answers, none of them reached the vulnerability value of 1 (none of the experts experienced an inundation depth which caused the necessity of completely substitute an element). This can be due to the fact that we asked to ignore structural damages: it is easy to imagine that a flood, before causing so huge damages to all non-structural building elements, destroys its structural elements.

A double confront can be done about the curves: on one side basing on their dependence on event duration; on another side, considering their variation with materials' improvement and how this influence also the passage between short and long duration.

In Figures 47 and 48 are reported the curves for the three classes of materials' quality, grouped for short and for long duration event.

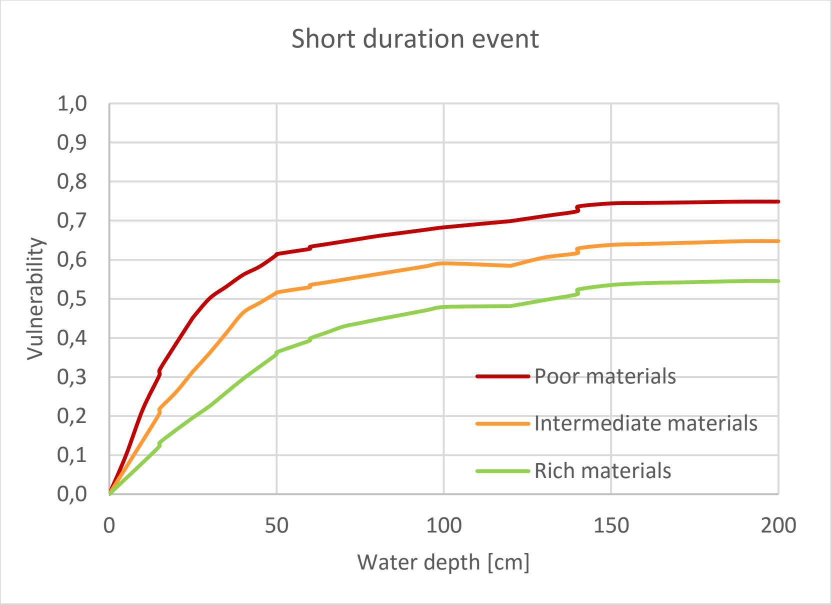

Figure 47. Comparison among curves for poorly finished, intermediate and richly finished buildings (short duration event).

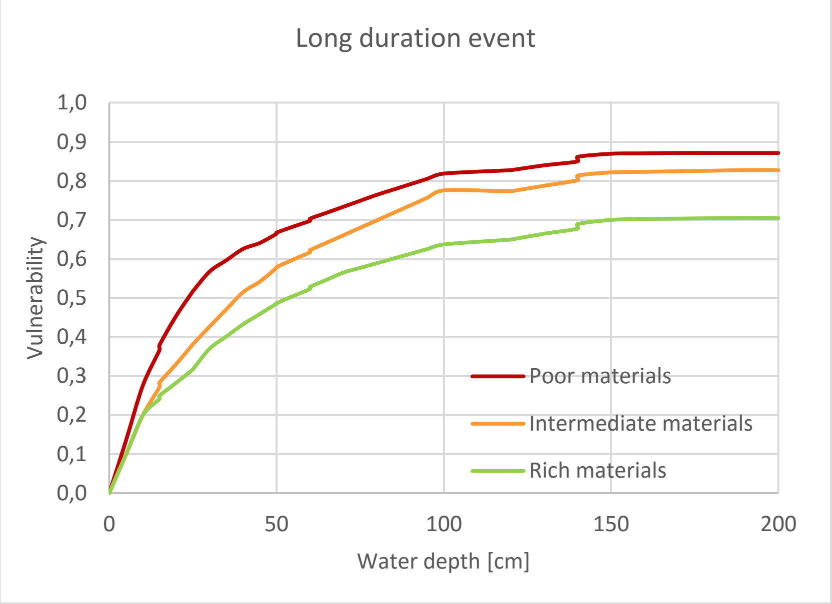

Figure 48. Comparison among curves for poorly finished, intermediate and richly finished buildings (long duration event).

The passage from poor to rich materials, as expected, corresponds to a decrease in relative damage, as better material suffer less flood damage in respect to poor ones.

This reduction is higher in short duration events, because on one side poor materials suffer huge damages yet for short duration of water contacts and on the other side good materials often need a simple clean-up intervention in these cases. It is instead lower for long duration events, because over a certain threshold poor materials reach a maximum damage (for us, it corresponds to the necessity of substitute the corresponding element), while rich ones go on suffering the consequences of water contact.

Although this damage reduction, the passage to rich materials implies also the disruption of more expensive objects, so that passing from relative to absolute curves (by multiplying them for elements' values), this tendency could invert.

6.4 Vulnerability analysis

The last step of a vulnerability analysis consists in joining the information on hazard, assets at risk and vulnerability in order to obtain a classification.

When available, information on the values of entities at risk allow the passage from vulnerability to risk (attended damage).

The exposure classification, instead, does not allow for a quantitative estimation of flood risk, but provides strategically significant indications. Comparing exposure and vulnerability maps it is possible to identify immediately the buildings with associated high vulnerabilities or, vice versa, to know immediately the vulnerability associated to sensitive areas. Moreover, as same vulnerability curves are associated to same featured buildings, the only way to know if they cover different roles is consulting their exposure class.

In this work, vulnerability assessment has been implemented in a GIS environment relating buildings-use and building internal inundation depth to the appropriate vulnerability curve.

Buildings data have been presented (in shape file format) as individual polygons with associated their exposure class as an attribute identified by a number. Each number in the building-use raster corresponds also to the vulnerability curve for that building typology. Each curve has been represented by a number of discrete pairs of flood depths and vulnerability values. The vulnerability for each cell has been finally calculated by using these functions to relate the flood depth to the damage.

Given the numerous sources of uncertainty in vulnerability assessment, it was decided to group its values in classes. In particular, as in Thakur et al. (2012), vulnerability intervals of 0,2 have been chosen to describe the progressive suffered damage. The corresponding scale of vulnerability is reported in Table 12.

Table 12. Vulnerability classes introduced by Thekur et al. (2012), modified.

Vulnerability	Description
0: No damage to wall, floor and roof materials	No damage; no repair or replacement
0,2	If either wall, floor or roof materials is half-damaged. No replacement needed only but repairing possible.
0,4	If two materials (among wall, floor and roof) are half-collapsed; no replacement needed but repairing possible
0,6	If any two materials (among wall, floor and roof) are half-damaged (repair) and one fully damaged (replacement)
0,8	If any two materials (among wall, floor and roof) are having total collapse and the other one is half collapsed. If those two materials might be needed replacement and other one
1: Total collapse	Total collapse; total replacement

The results of vulnerability analysis have been reported both in maps and in a Exposure-Vulnerability matrix, able to give us an idea of the actual situation of a catchment or to compare different scenarios. In each cell of the matrix, it can be seen which percentage of the total area is associated to each vulnerability class, distinguished for the different exposure classes.

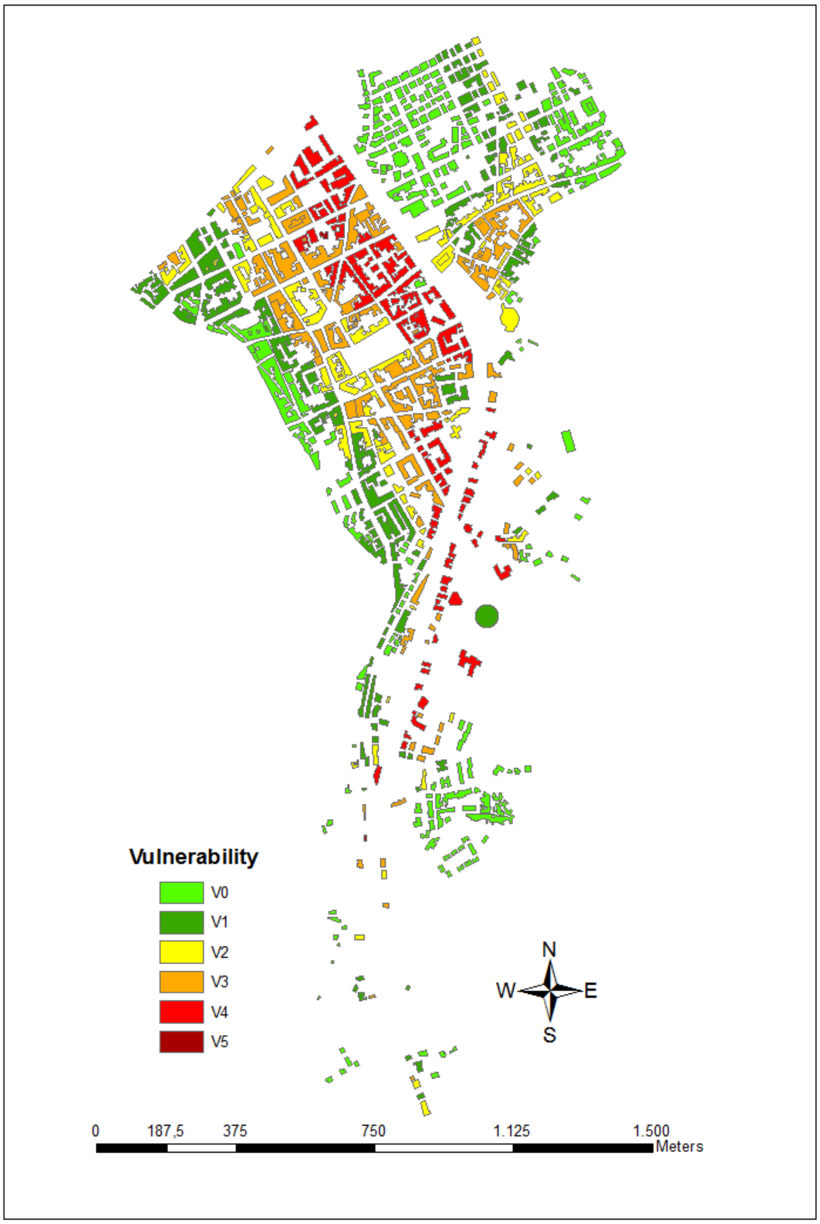

Figure 49. Vulnerability map.

Table 13. Exposure-Vulnerability matrice.

	E-V	V0	V1	V2	V3	V4	V5
E1	**E1.5.3**	-	0,24%	-	0,27%	-	-
	E1.5.2	0,67%	0,21%	0,12%	0,20%	-	-
E3	**E3.1.3**	1,20%	0,22%	0,10%	0,03%	-	-
	E3.2.4	1,88%	1,45%	0,31%	4,01%	0,99%	-
	E3.2.3	0,90%	4,44%	0,07%	0,73%	-	0,24%
	E3.2.1	4,38%	4,74%	3,14%	3,69%	5,98%	-
	E.3.2.0	-	0,39%	0,29%	0,06%	-	0,20%
E4	**E4.3.6**	2,53%	1,24%	0,66%	3,36%	0,81%	-
	E4.3.3	20,53%	8,76%	5,82%	3,66%	2,77%	-
	E4.3.2	1,31%	0,51%	0,10%	0,67%	0,78%	-
	E4.3.1	0,01%	-	-	-	-	-
	E4.2	0,51%	0,25%	-	0,02%	-	-
	E4.1.3	0,18%	0,12%	0,44%	0,18%	0,38%	-
	E4.1.2	0,78%	0,90%	0,09%	0,03%	0,40%	-

The construction of E-V matrix allows both to understand the actual situation of a catchment (and the possible consequences of a flood event) and to study the effectiveness of non-structural measures for a site, just studying how their implementation modifies the distribution of elements at risk inside it.

Conclusions

Risk management is becoming the dominant approach of flood control policies throughout Europe. The EU Flood Directive underlines the importance of prevention-oriented approaches, adopting early-warning systems, flood forecasting technics, land use regulation. But the use of prevention measures that do not interfere on flood's features require the elaboration of methodologies and strategies aimed at verifying their effectiveness.

While many studies addressed to the evaluation of flood Hazard has been developed during last years, studies addressed to the evaluation of flood Vulnerability (interpreted as the relative damage associated to elements at risk) are few and reliability of their results is far from being satisfying.

Even if different damage assessment methods can be used, in fact, limitations in available data and knowledge on damage mechanisms are mentioned as the main obstacles to the derivation of uncertainties associated. Moreover, the majority of these methodologies are addressed to the estimation of direct tangible damages, often neglecting indirect ones and almost ignoring intangible ones.

Generally, the assessment of direct economic damages foresees three steps, each having potential for improvement. The first is the classification of elements at risk by pooling them into homogeneous classes. The second regards the Exposure analysis and asset assessment by describing the number and type of elements at risk and by estimating their asset value: data can be derived from land use maps, field surveys or official statistics at different spatial scales. Unfortunately, compared to the resolution and accuracy of flood hazard modelling, even the most detailed asset assessments are regarded as coarse, often leading to a spatial mismatch between hazard and exposure data: this mismatch could require great efforts in disaggregation. The last step in direct damage assessment is the susceptibility analysis by relating the relative damage of the elements at risk to the flood impact.

According to Italian regulations, risk assessment in Sicily is carried out by means of the use of matrices providing flood hazard and flood risk in function of the event return period, the inundation depths and the exposure classes of elements at risk. The Exposure classes refer to a nominal value attributed to the elements in function of their strategic, economic and functional role (no assets values are indicated), while Vulnerability is considered constant and equal to 1.

The idea of bypassing the assets' monetary value, actually, may allow to reduce uncertainties when strong databases supporting the analysis lack and to avoid both in depth economic studies required to derive them and eventual disaggregation necessary to downscale the classes. Conversely, fixing the Vulnerability default value equal to 1 inhibits any assessment of its variations and, than, any possible comparison among different combinations of non-structural measures aimed at evaluating their effectiveness.

Both the building density and the strategic importance of the buildings influence Exposure; Vulnerability, instead, is influenced by their constructive characteristics, by the implemented security measures or, vice versa, by the criticalities that make them suffer strong damages for few flood volumes. Vulnerability is therefore an intrinsic building feature: the same vulnerability curves may be assigned to buildings belonging to different exposure classes. That is why it is important not to neglect any of the two variables.

This thesis deals with a new method for a qualitative evaluation of flood risk, based on the definition of Exposure classes and the derivation of flood Vulnerability curves for buildings. The crisscross study of these variables seems the only possibility to carry out a risk analysis when damage data lack or are unreliable and estimation of assets' values is impossible.

The methodology has been developed in four steps: hydraulic modelling to derive the hydrodynamic characteristic of the flood event studied; particularization of the Exposure classes provided in the Flood Risk Plan for Sicily; derivation of vulnerability curves through a synthetic approach; vulnerability assessment for different Exposure classes, referring to a flood occurred in Sicily.

Given the numerous sources of uncertainty in vulnerability assessment, it was decided to group its values in classes, varying from no damage to total disruption.

Results are reported in vulnerability maps, but also in an Exposure-Vulnerability matrix, able to describe the actual situation of a catchment or to compare different scenarios. In each cell of the matrix, it can be seen which percentage of the total area is associated to each vulnerability class, distinguished for the different exposure classes.

Referring to vulnerability (and considering its classes instead of single values) allows to estimate the possible consequences of an event even in those catchment where the lack of damage data does not allow the construction of damage curves.

The approach developed in this thesis intended to be a contribution in the general challenge represented by flood risk management and, in particular, by vulnerability assessment aimed at the evaluation of non-structural measures effectiveness.

It is worth to underline that general gaps still affect scientific studies on this topic.

Although improvements have been made over last decades, considerable uncertainties still exist in all parts of cost assessments. Models validation is scarcely performed and uncertainties often neglected: an important effort could come from the identification of the main sources of uncertainty, in order to handle them and communicate residual uncertainties in cost estimates to decision makers.

These shortcomings depend inevitably from the already mentioned lack of sufficient, comparable and reliable data. Much larger efforts should be made for empirical and synthetic data collection in order to provide consistent, reliable and comparable data to scientists and practitioners.

On the other side, a better understanding of the processes leading to damage could led to the inclusion of more influencing variables in the analysis and to extend it to improve estimation of indirect and intangible losses.

Last but not least, in order to answer the requests of EU Directive of flood risk management, the goal to pursue is a general homogeneity both in databases development and in mitigation costs definition.

As scientists and technicians, in fact, our hope is to provide appropriate tools, guidance and knowledge to support decision makers when integrating cost assessment into their decision making process.

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