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Application of a model to the evaluation of flood damage

**F. Luino · C. G. Cirio · M. Biddoccu · A. Agangi ·
W. Giulietto · F. Godone · G. Nigrelli**

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Abstract This paper presents the initial results of a common methodology for the evaluation of damage produced by a flood. A model has been developed for flood damage estimation based on a geographic information system (GIS). It could be used by land administration bodies and insurance companies to manage flood-related damage data. The model simulates flood scenarios and evaluates expected economic losses from the impact of floodwaters on exposed elements, through the application of a computational model elaborated by GIS. During the development of the model, the Boesio Stream, a small watercourse flowing into Lake Maggiore (Lombardy, northern Italy) which was recently affected by a flash flood, was used as case study to test and calibrate the methodology. The method could be used either as a forecasting tool to define event scenarios, utilizing data from events simulated with a hydraulic model, or for real-time damage assessment after a disaster. The approach is suitable to large-area damage assessment and could be appropriate for land use planning, civil protection and risk mitigation.

Keywords Flood · Damage evaluation · Stage–damage curves · Hydraulic modelling · GIS

1 Introduction

As they are the most common form of natural disaster, floods are of great interest to the general public. Every year, severe flooding affects many regions of the world. The International Emergency Disasters Database EM-DAT recorded 238 floods in Europe between 1975 and 2001 [3]. In the decade 1980–1989, 1,940 people died as a result of floods and 417,000 were made homeless [4]. In August 2002, floods in the Elbe, Moldava and Danube Basins provoked damage estimated at more than three billion Euros in the Czech Republic and more than nine billion in Germany. The European Union defined the

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F. Luino (✉) · C. G. Cirio · M. Biddoccu · A. Agangi · W. Giulietto · F. Godone · G. Nigrelli
Italian National Research Council, Research Institute for Geo-hydrological Protection,
Strada delle Cacce 73, 10135 Turin, Italy
e-mail: fabio.luino@irpi.cnr.it

event as a “severe catastrophe” and for the first time created a solidarity fund. The EU granted 728 million Euro to the regions of Germany, Austria, the Czech Republic and France affected by floods.

Several institutions have developed methodologies designed to quantify flood losses in their specific domains; however, there is no standard procedure to determine a global figure for economic impact. Nevertheless, in 2004 the European Union inaugurated the ‘Damage’ Project [2] in response to the need of European civil protection services to have a common methodology for the evaluation of damage produced by disaster. One of the project’s goals is to provide public administrations such as municipal, provincial and regional governments with a tool designed to help them obtain and manage information on damage. For this purpose a GIS-based model was created to simulate flood events and evaluate consequent economic losses. The traditional approach to damage assessment consists of detailed field survey with the aim of establishing the actual loss. In recent years, attempts have been made to define methodologies for the rapid assessment of damage in the aftermath of a disaster.

The main objective of the present study was to devise a method that could enable real-time assessment of potential economic direct loss due to a natural process. The method requires a thorough knowledge of the local area coupled with descriptions of some physical aspects of natural events. When a catastrophic natural event of a given intensity affects a particular area, the value of economic losses connected to direct damages to goods depends on the number and economic value of the units of each element in the area and on the degree of damage to the exposed units, commonly defined as vulnerability (varying from 0 = undamaged to 1 = completely destroyed). The economic worth of loss can be defined as:

$$\begin{aligned}&\text{DIRECT ECONOMIC LOSS}\\&\quad=\Sigma_i\left(\text{UNIT VALUE}_i \times \text{No. of units EXPOSED ELEMENT}_i \times \text{ DAMAGE DEGREE}_i\,[\%]\right).\end{aligned}$$

2 Description of the methodological model and its application to a case study

The methodology for flood damage estimation can be summed up by the following points (Fig. 1):

- description of the event: definition of flooded area and water level (this definition will be implemented by real-time measurements or by simulation of events with a hydraulic model),
- identification of damaged assets in the flooded area,
- evaluation of the degree of damage to the exposed elements as a function of the magnitude of event as identified from measurement of floodwater depths,
- attribution of economic value to exposed assets,
- quantification of economic losses by multiplying the economic value of damaged assets and the degree of damage.

The method can be used to estimate the damage from the impact of floodwaters on exposed elements (direct damage) and to quantify the resulting economic loss (tangible damage). Indirect and intangible damage assessment is beyond the scope of this model.

During the development of the model, a case study was utilised to test and calibrate the methodology. Because of its relatively small extent (45 km^2), the Boesio basin of northwest

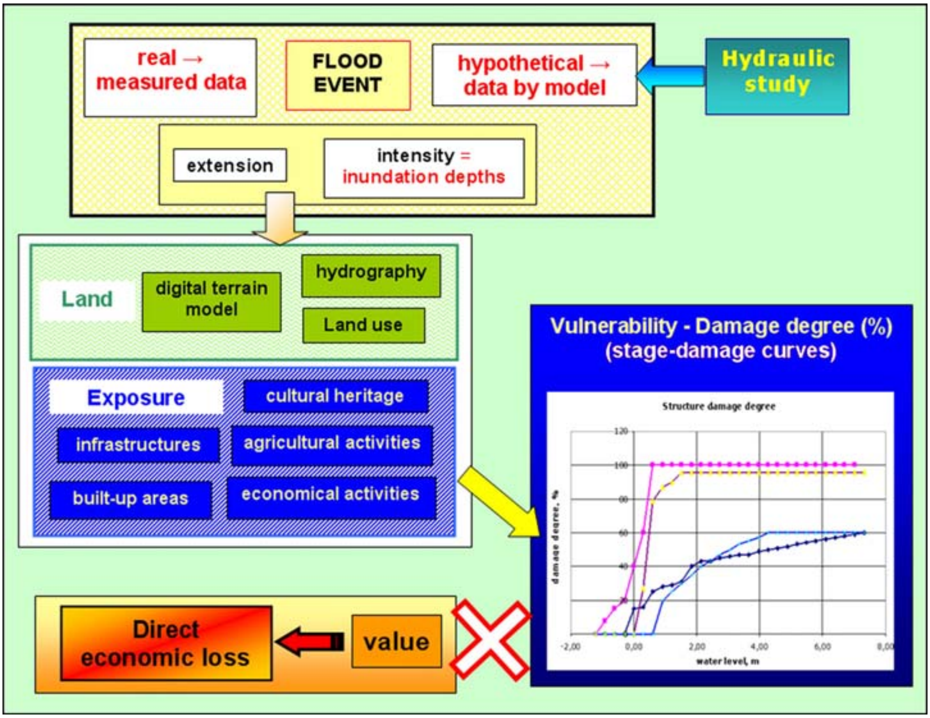


Fig. 1 Conceptual model of flood damage assessment

Lombardy Region was chosen as the study area (Fig. 2). The basin has suffered intense human pressure on its environment and a recent severe flooding event, for which information about damage was well documented. It also has good availability of territorial data and historical information about the damages from past disasters. The methodology was applied to the case study in order to estimate flood damage to structures. Damage to agriculture and mobile goods was not taken into account.

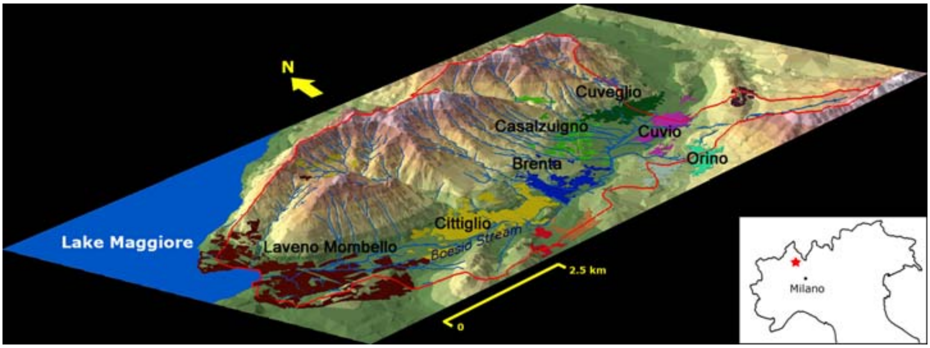


Fig. 2 3D location map of Boesio basin: the boundary is shown as a *red line*

2.1 Geological data base

The application of the study methodology was restricted by the availability of data, which needed to be organised into a GIS database for the study area. The data were gathered and divided in two categories: (a) layers containing spatial information on topography, altimetry (digital terrain model), hydrography and hydrology; and (b) layers pertaining to anthropogenic presence, exposed assets and land use. As a rule, the more detailed the information, the greater the precision of the assessment of potential losses.

2.2 Typology of flood events

The method can be applied to two types of floods. First, real events can be used by measuring flooded area and inundation depths in the field. This method permits a quick estimate to be obtained of the approximate extent of damage during or immediately after an event. Secondly, scenarios of the event can be founded on hydrological analyses. The characteristics of the event are obtained through hydraulic models and the methodology is applied in order to forecast the consequences of a given future event.

In May 2002 the Boesio basin was struck by a severe hydrometeorological event. The main stream and its tributaries overflowed across urbanised and rural areas and severe damage occurred to houses and factories. This flood event was chosen as the reference event in order to test and refine the methodology. A back analysis was performed to verify process validity and check the reliability of the results. For this reason, the event was investigated thoroughly using surveys, interviews with local inhabitants, and data acquisition from the data bases of local administrations. The inundation limits and levels reached by floodwaters were identified and graphically represented as GIS layers. Data about event-related damage and losses were collected and processed. For each inundated building, information was gathered about its structural typology and use, the ground-floor surface area, its economic value, flood levels reached on the ground floor, damage levels and consequent economic losses.

2.3 Hydrologic–hydraulic study

Territorial and hydrological data for the Boesio basin were used to create a rainfall–runoff model for the Cittiglio area. The model made it possible to calculate stream discharge resulting from rainfall amounts of given return periods. The expected discharge value was then input to a one-dimensional hydraulic model in order to determine floodwater levels and thus create an event scenario. Past inundation data were essential in setting the parameters for the model.

2.3.1 Step 1: territorial and hydrologic data collection

Territorial data Topographic information about the Boesio basin was obtained from a digital terrain model (DTM) with a 20 × 20 m mesh size, and from topographic maps at a scale of 1:10,000 created by the Regione Lombardia (Regional Government of Lombardy). The stream basin was divided into six sub-basins according to the position of minor tributaries and confluences. The morphological characteristics of each sub-basin, and of the whole basin, were then identified, with emphasis on those features that would influence the hydrological behaviour of the stream, especially the concentration time.

In order to perform both a hydraulic analysis of the Boesio Stream and flood scenario modelling, an accurate description had to be made of the riverbed geometry and adjacent floodable areas. A DTM was obtained by processing photogrammetric data from aerial photographs taken in April 2005 over the Boesio Stream and its floodplain. In order to create a topographic map with elevation points and contour lines at 0.5 m intervals, the DTM (*.dxf* 3D format) was interpolated using "break-lines" that mark sudden changes in slope on the topographic surface. Upstream and downstream of Cittiglio, 237 sections were marked every 20–30 m across the riverbed, including the entire floodplain (Fig. 3). Others were marked upstream and downstream of bridges, protective embankments, bends and confluences. Sections were exported as a *.dxf* file that could be used in CAD and GIS environments. For use in the hydraulic modelling software HEC-RAS®, the file was converted into an *.xyz* file.

Hydrologic data The simulation of a real event needs discharge measurements during the flood or, if these are not available, rainfall data measured by raingauges located in the basin or in the adjoining catchments. If rainfall measurements only are available, a rainfall–runoff model must be applied during the hydrological analysis. The simulation of a hypothetical event requires the use of past series of discharge or rainfall data. Serial data sets on intense rainfall in the past were not available for the Boesio catchment. Therefore, intense precipitation was analysed for adjoining basins, where intense rainfall data had been collected by raingauges. In some cases, the old recording raingauges were replaced with automatic ones that record data every 15 or 30 min. Measurements about past flood events are also useful for setting the hydraulic parameters of the model and for testing it.

2.3.2 Step 2: hydrological analysis

Hydrological analysis aims to predict the expected discharge of the Boesio Stream for a given return period, using a rainfall–runoff model if only rainfall measurements are available.

Inflow definition In defining a rainfall–runoff model and calculating the rainfall intensity–duration curves, the lack of 30 years of intense rainfall measurements in the Boesio basin

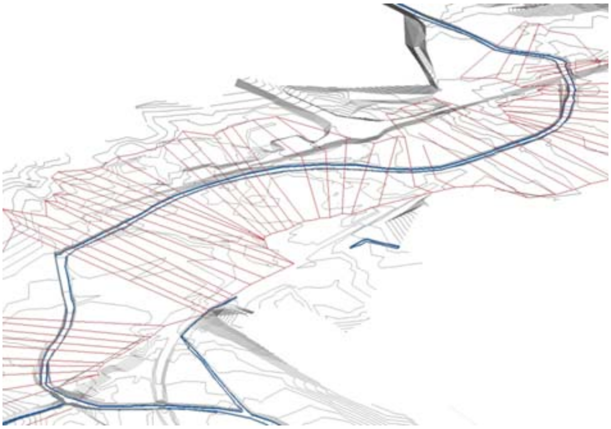


Fig. 3 Cittiglio municipality: a 3D view of the Boesio valley bottom, represented by *contour lines*. The cross sections of the Boesio Stream and floodplain are shown in *red*

was a considerable disadvantage. Two approaches were utilised to define these curves: (a) interpolation methodology [8], using Kriging of the regularised series of rainfall measurements, as recorded by raingauges in the adjacent basins; and (b) the methodology developed by the VAPI Project (a CNR-GNDCI project for flood evaluation in Italy, [2]), consisting of a regional statistical model based on a TCEV (Two Component Extreme Value) distribution, which uses geostatistical estimation of rainfall or discharge at sites without raingauges.

Runoff coefficient. This essential parameter was defined for each sub-basin according to two methodologies: (a) the 'rational' method uses information about land use and slope in the basin; and (b) the method proposed by the US Soil Conservation Service (SCS) [12] is based on the determination of the curve number, which is used in the SCS equation for peak discharge. The curve number is based on the hydrological soil group and ground cover and can be determined from a special table.

Determination of peak discharge values. The final phase in the application of the rainfall–runoff model is the calculation of the peak discharge values for given return periods. It is essential to define the *time of concentration*. This can be determined according to various equations that use morphologic parameters of the basin. In the present study, the equations propounded in [6, 7, 9, 10, 14] and [12], were used for each sub-basin. The results differed considerably, so that for each sub-basin the lower times of concentration, and thus the higher discharge values, were used.

Two methodologies were used to determine *peak discharge* values: the 'rational' method and SCS method [12]. Discharge values were calculated for each of the six sub-basins for return periods of 20, 100 and 200 years. The rational equation required knowledge of morphologic variables of the basin, including the runoff coefficient c, the time of concentration T_c, and the a and n values (parameters of the "rainfall–intensity–duration curves"). As input to the SCS equation, the SCS method needs the curve number of the basin, the a and n values and the time of concentration.

2.3.3 Step 3: hydraulic steady flow modelling

In the study area, one-dimensional steady flow modelling was performed using HEC-RAS. To execute the calculations, the software required data on the morphology of the riverbed and adjacent floodable areas, along with cross sections, distances between sections, Manning coefficients, discharge values and topographic contours. Modelling was carried out using the discharge values calculated according to the rainfall–runoff model for floods with 20- and 100-year return periods. The output was the absolute free water level in metres above sea level. The flood levels were marked on all sections (in *.dwg* format). In order to delineate the floodable areas, the intersection between the free water surface and the topographic surface was drawn on a map.

2.3.4 Step 4: event scenarios

A three-dimensional model of the floodwater surface was created using data from the 237 sections: the result was a topographic representation of the flooded area for the scenario under consideration. These data were used as a layer in a GIS application, making an intersection with the DTM and thus obtaining a three-dimensional view of the valley bottom during a flood. The model was calibrated with data from the flood that occurred over the period 2–5 May 2002 and by comparing the estimated peak discharges with the measured ones. A comparison was made between the flood-prone area obtained by the model and the area flooded in May 2002, as reconstructed using aerial photographs and surveys. The model corresponded closely to the real event (Fig. 4). In general, differences were caused by flooding of some of the Boesio's tributaries, which were not considered in the model.

2.4 Building vulnerability and stage–damage curves

By definition, vulnerability can be described as the degree of damage to a group of elements at risk resulting from a natural event with a given intensity. The degree of flood-induced damage to structures is determined by many factors, including water level, flow velocity, quantity of suspended and floating load, contaminants in the water and flood duration. The published literature [5, 11, 13] reports that the depth of flooding is often considered as the only factor indicative of the magnitude of flood events, which is a common simplifying assumption. Given a particular type of exposed element, a relationship can be defined between the depth of flooding and the losses incurred as a percentage of the element's total worth (i.e., the degree of damage, see Fig. 5).

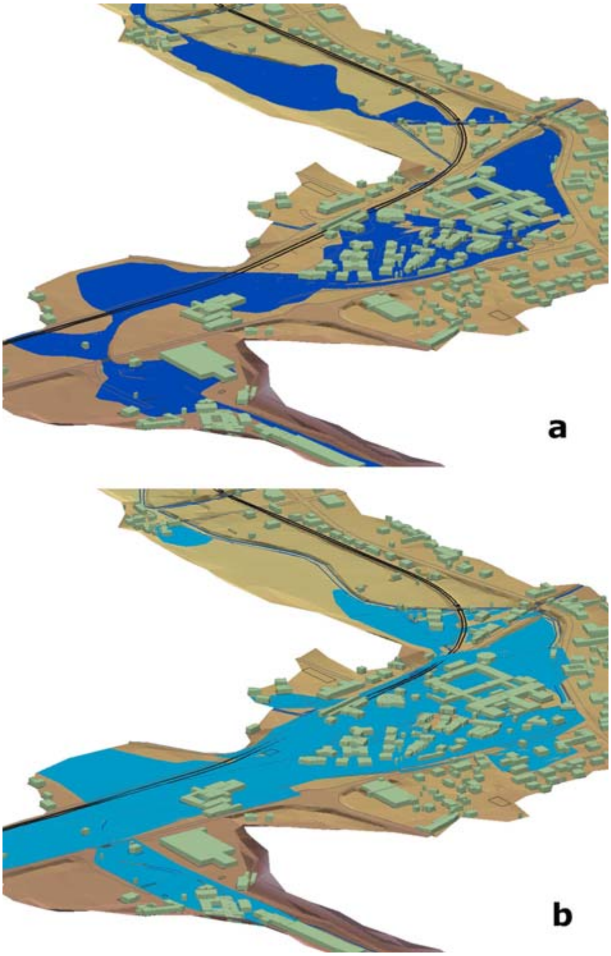


Fig. 4 Comparison of the flooded area resulting from: **a** the output of the one-dimensional model; **b** post-event surveys and photo-interpretation

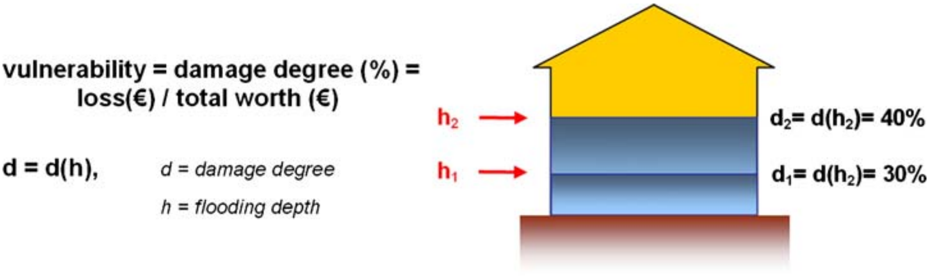


Fig. 5 Given a particular type of structure, different water levels are uniquely related to different degrees of damage

Coupling the value of inundation depth with degree of damage enabled us to characterise the direct effect of floodwater on different types of exposed elements and to define curves which are generally referred to as *stage–damage curves* (they are also called *loss functions* or *vulnerability functions*). Each curve should be studied in terms of the effect of floodwaters on a particular type of exposed element (such as construction type, building dimensions or road access conditions) and it can be utilised to simulate damage caused by potential future floods. Nevertheless, it can be difficult to extrapolate data gathered from place to place to different building types and contents. For this reason, different curves should be created for different geographical areas and then applied to limited and relatively homogeneous regions.

The data collected for each structure inundated by the May 2002 flood in the Boesio basin were employed to develop stage–damage curves. Residential buildings with basements made up the bulk of the structures damaged. Hence, a stage–damage curve was generated only for this type of building (Fig. 6). An empirical approach was followed, using information on losses measured after the flood combined with estimates of water depths. The curves described the effect of floodwaters on masonry, floor, doors, windows and installations associated with each structure, and did not consider mobile goods.

For each building the degree of damage was calculated by dividing the economic cost of repairing structural damage by the value of the ground floor and basement (see section on the economic evaluation of buildings), as follows:

$$\textit{damage degree (\%)} = \textit{loss (€)} / [\textit{ground floor value (€)} + \textit{basement value (€)}]$$

About 100 pairs of values of water level and damage degree were plotted on a dispersion diagram and a stage–damage curve was obtained by linear interpolation. The flood depth required to develop the curves included both flood levels in basements (negative values) and the depth of water above the ground surface (positive values).

2.5 Economic evaluation of buildings

If damage is to be quantified it is essential to make a preliminary evaluation of the elements exposed to flood risk. With regard to buildings, a detailed evaluation was made of each floodable structure. Estimation of the value of buildings and contents was based on knowledge of the type of structure and its use. For this, the study area data base required a layer designed to contain the information and characteristics of all buildings, including usage, structural type, number of floors, presence or absence of a basement and ground floor surface area.

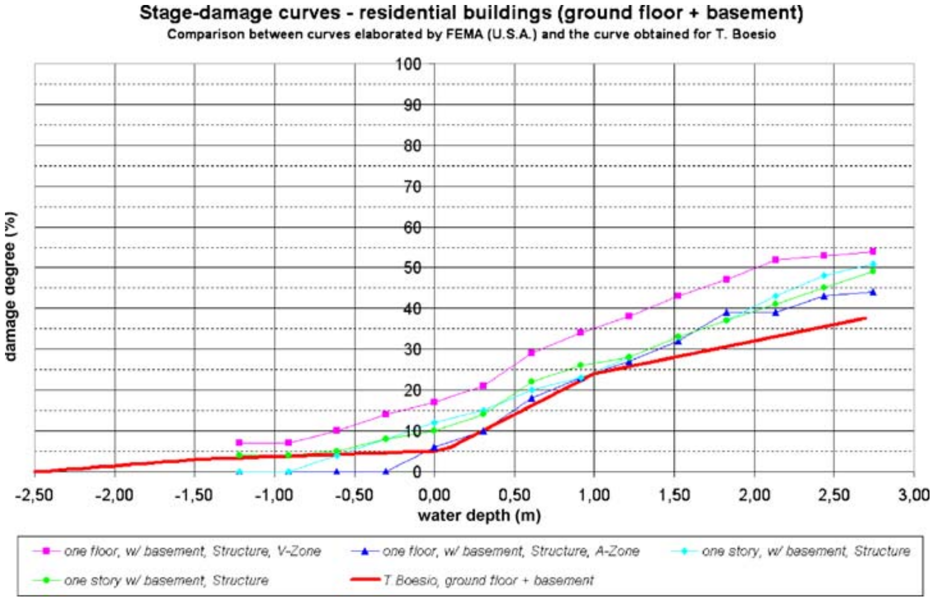


Fig. 6 Stage–damage curves for residential buildings. Comparison between curves constructed by the Federal Emergency Management Agency in the USA (after [5]) and the curve obtained for the Boesio Stream in Lombardy

In Italy, considering only the structure and not the content, the unit value of buildings (€/m^2) is given by the *Banca dati delle quotazioni immobiliari*, (real estate and property price database) published in 2005 by the Local Real Estate Market Analysis Services (Osservatorio del Mercato Immobiliare dell'Agenzia del Territorio, [1]). The estimation of a building's unit value is based on its geographical location, usage and typology. The database furnishes a minimum and maximum value for each type of building and is updated every 6 months. It was used to assign a unit value to the buildings in the Boesio basin, calculating the average between the minimum and maximum values estimated for each type of structure.

In the Boesio basin the ground floor and basement are the only parts of a building that are vulnerable to flood damage. In general, floodwaters reach a maximum height of 2 m. For this reason, and for each building in the flood-prone area, when estimating exposure only the value of the ground floor plus the basement was considered. The value of the ground floor was calculated by multiplying its surface area by the unit value. Following the evaluation criteria of the US Federal Emergency Management Agency [5], the basement value was expressed as a percentage of the total value of the building. In the study area, the value of the basement (or cellar, boiler room or garage) was estimated to be about 25% of that of the ground floor.

2.6 Calculation of expected building damage

During the development of the methodology, a computational model for the assessment of expected flood damage was created in a GIS environment. Raster information layers in grid format were employed for this purpose. Using ArcGIS software (ESRI©) and its Spatial Analyst extension, a geographical analysis was carried out by comparing different raster datasets to obtain information by means of superposition and combination. In order to calculate economic damage to residential buildings caused to Cittiglio by the May 2002 flood, the computational model was applied to the study area

The following information layers stored in the database were utilised:

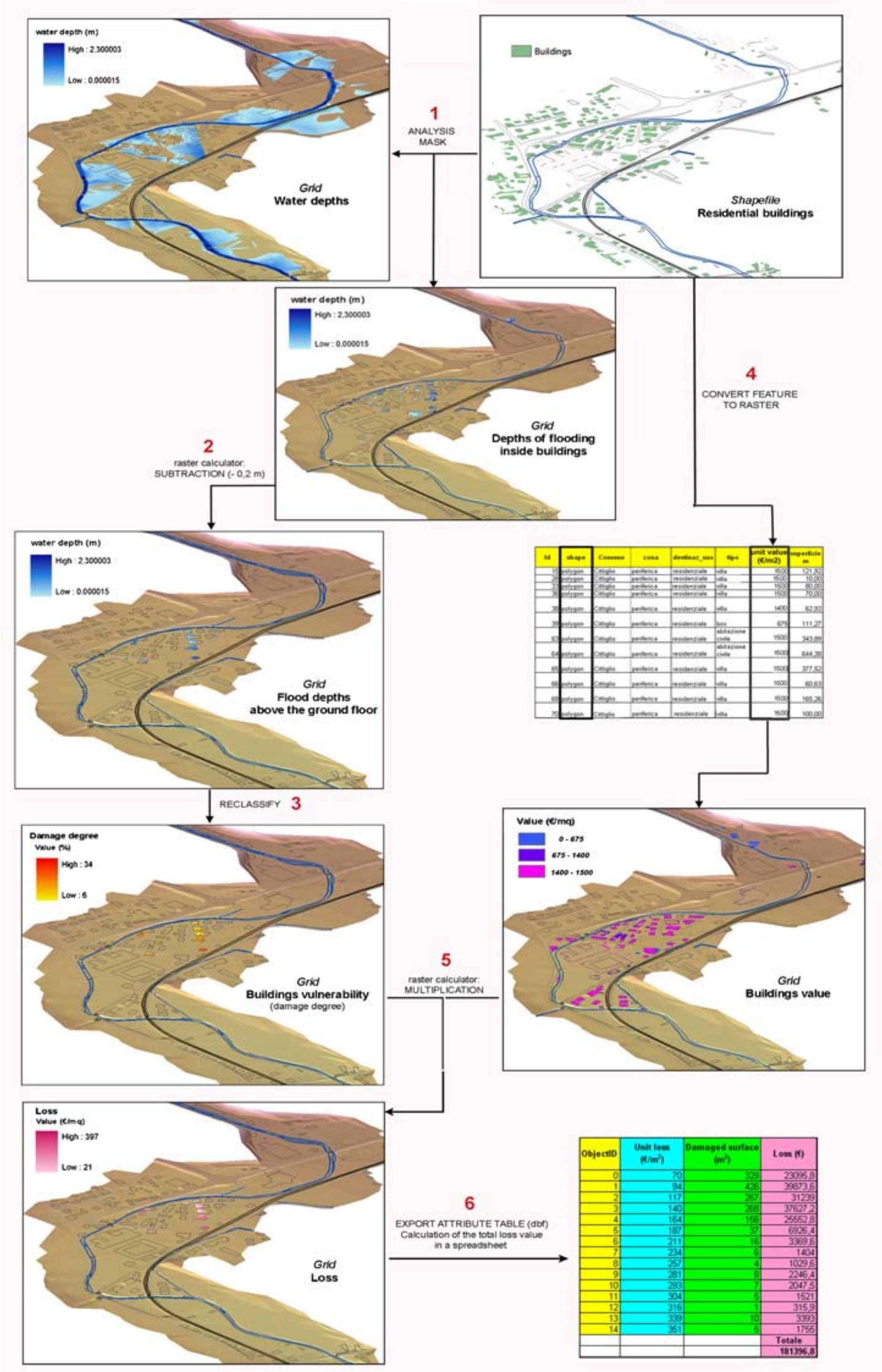
- Digital terrain model.
- Water surface elevation (expressed in metres above sea level), calculated by hydraulic modelling. In this study calculated values of water depth were used because they were more uniformly distributed than those measured in the field after the May 2002 flood. Moreover, not enough data on floodwater levels were available for built-up areas and buildings to enable a perform a reliable interpolation to be made.
- A polygonal layer of built-up areas, with buildings classified by usage, typology and economic unit value in €/m^2 (ground floor unit value plus basement unit value).

All the layers compiled as shapefiles were converted into a grid format. In order to obtain a one-to-one ratio between the cells, the same cell size was set for each of them. This enabled cells from different grids to be matched with one another directly and operations to be computed between grid values. Considering the resolution of the data source, a cell dimension of 1 m was chosen in the conversion of shapefiles to raster files. This is appropriate to any object or land form with sufficient detail. The built-up area shapefile was first divided into different layers, each of which contained structures that belonged to a single category of use, such as residential, production or trade. Only the shapefile of residential buildings was used subsequently. For all flooded locations, the ground surface elevation grid (DTM in metres above sea level) was subtracted from the calculated water surface elevation grid (also expressed in metres above sea level), which resulted in a grid that contained the flood levels above the mean ground surface (metres).

The expected economic loss was then calculated using the following operations (see Fig. 7):

(a) The shapefile of residential buildings was used as an analytical mask over the raster dataset of water depths. This produced a grid of the depths of flooding inside the buildings.
(b) To compensate for the average difference in height between the ground surface level and the road level, 0.2 m was subtracted from the grid. This produced a grid of flood levels above the ground floor.
(c) The representation of the vulnerability of residential buildings was accomplished through a reclassification of the grid of the depths of flooding inside buildings. This operation allowed a degree of damage to be assigned to each water level according to the values of the stage–damage curve for residential buildings.
(d) The shapefile of residential buildings was converted to raster format by selecting the field of the related unit values, in €/m^2 (ground floor plus basement unit values). This produced a grid of the value of buildings.
(e) The raster datasets of unit values and degrees of damage were combined by multiplying their values. The resulting grid defined the potential loss values in every cell and its attribute table contained the loss value classes and the related number of cells.
(f) The table related to the loss grid was exported and processed in a spreadsheet. Using simple addition and multiplication, it was possible to appraise the loss value for residential buildings in Cittiglio.

The computed loss amounted to €181,000. Losses related to structural damage to residential buildings and officially declared by Cittiglio Municipality amounted to



Id	shape	Comune	zona	destinaz_uso	tipo	unit value (€/m2)	superficie m
15	polygon	Cittiglio	periferica	residenziale	villa	1500	121,82
26	polygon	Cittiglio	periferica	residenziale	villa	1500	10,00
33	polygon	Cittiglio	periferica	residenziale	villa	1500	80,00
36	polygon	Cittiglio	periferica	residenziale	villa	1500	70,00
38	polygon	Cittiglio	periferica	residenziale	villa	1400	62,92
39	polygon	Cittiglio	periferica	residenziale	box	675	111,27
63	polygon	Cittiglio	periferica	residenziale	abitazione civile	1500	343,89
64	polygon	Cittiglio	periferica	residenziale	abitazione civile	1500	644,38
65	polygon	Cittiglio	periferica	residenziale	villa	1500	377,62
66	polygon	Cittiglio	periferica	residenziale	villa	1500	60,63
69	polygon	Cittiglio	periferica	residenziale	villa	1500	165,26
70	polygon	Cittiglio	periferica	residenziale	villa	1500	100,00

ObjectID	Unit loss (€/m^2)	Damaged surface (m^2)	Loss (€)
0	70	329	23096,8
1	94	426	39873,6
2	117	267	31239
3	140	268	37627,2
4	164	156	25552,8
5	187	37	6926,4
6	211	16	3369,6
7	234	6	1404
8	257	4	1029,6
9	281	8	2246,4
10	293	7	2047,5
11	304	5	1521
12	316	1	315,9
13	339	10	3393
14	351	5	1755
			Totale
			181396,8

Fig. 7 Calculation of expected flood damage losses

€110,000. Taking into account the level of approximation of the calculation model and the need to calibrate the method with other case studies, the difference between the real loss and the calculated value is ascribable to the damage assessment criteria. Only damage to principal residences that cost more than €2,500 for was considered refundable and hence reported, which makes a total loss of €110,000 clearly an undervaluation.

3 Findings

The proposed methodology meets the need of public administrators to obtain a rapid but approximate estimate of damage after a disaster. It was designed to be used in different geographical contexts, and where different basic information is available. With the aid of improvements, such as the elaboration of new stage–damage curves for new types of exposed elements and the application to other case studies, this method could become a useful tool for decision-making in land management. It could be used as a forecasting tool, to define event scenarios or for rapid assessment of damage after a disaster caused by a natural hazard.

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Dr. Fabio Luino He received a degree in geology from Turin University in 1987, and is an Expert with the National Civil Protection and Emergency Service, studying urbanized areas affected by natural processes and evaluating geological risk in urban planning. He is also in charge of the "Territorial Data Management" section, including the library, photographic and film libraries, historical archive and map collection. Scientific Secretary and Editor of the Conference Proceedings for the International Conference "Prevention of Hydrogeological Hazards: the role of scientific research" (Nov. 1996). The 1999 visiting scientist in the ITC of Enschede (The Netherlands). He is currently a researcher of the Italian National Research Council, Research Institute for Geo-hydrological Protection located in Turin. His research interests include floods, landslides and muddy-debris flows. He is studying these natural processes from a geomorphological and historical perspective with an emphasis on urban planning applications.

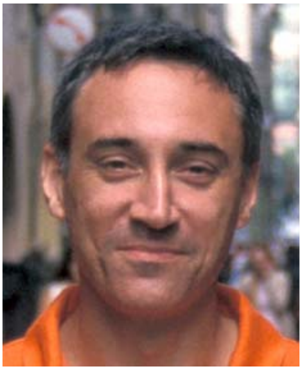
Chiara Giorgia Cirio She graduated in Geology with first-class honours at the University of Turin in November 2002. Since 2004 she has collaborated as fellowship holder at the Research Institute for Geohydrological Protection of Turin (IRPI Turin) of the Italian National Research Council. Her research interests include geomorphological studies in fluvial dynamic and muddy-debris flow processes, flood risk evaluation and damage estimation, and development of spatial and spatio-temporal databases. All her studies are based on GIS-based application and modelling.

Marcella Biddoccu Environmental engineer and fellowship holder at the Research Institute for Geo-hydrological Protection (IRPI-CNR) of Turin since 2005. Her research uses data collection and analysis to develop a methodology for flood damage evaluation and to create a data base of debris flow phenomena in Lombardy.

Andrea Agangi He graduated in Geology. His research interests include hazard and risk assessment, fluvial evolution in Alpine environment. He was a fellowship holder at the Research Institute for Geo-hydrogeological Protection (IRPI-CNR) of Turin from 2004–2006.

Walter Giulietto Geologist and fellowship holder at the Research Institute for Geohydrogeological Protection (IRPI-CNR) of Turin from 2004–2006. He is studying the interaction between ground instability in natural processes and human activities in fluvial environments.

Franco Godone Specialized technician at Research Institute for Geohydrogeological Protection (IRPI-CNR) of Turin since 1972. He is engaged in topographical and aerophotogrammetrical surveys and data analysis in the alpine regions.



Guido Nigrelli He is a Naturalist, studying pluviometric and climatic aspects of the hydrographic basins in northern Italy. He is also analyzing meteor-hydrologic characterization of extreme events.