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ORIGINAL PAPER

Multi-vulnerability analysis for flash flood risk management

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Abstract Vulnerability assessment implies a quantitative evaluation of the individual vulnerability components such as elements at risk, their physical exposure and social characteristics. Current approaches in vulnerability research are driven by a divide between social scientists who tend to view vulnerability as representing a set of socio-economic factors, and scientists who view vulnerability in terms of the degree of loss to an element at risk. To close this gap, a multi-dimensional vulnerability analysis has been undertaken focusing on flash flood hazards in Greece. To represent physical vulnerability, an empirical relation between the process intensity and the degree of loss was established. With respect to social vulnerability, an assessment was undertaken by means of empirical data collection based on a door-to-door survey. In general, both physical and social vulnerability was comparable low, which is interpreted as a result from (a) specific building regulations in Greece as well as general design principles leading to less structural susceptibility of elements at risk exposed, and (b) a relatively low economic loss leading to less social vulnerability of citizens exposed. It is shown that a combination of different perspectives of vulnerability will lead to a better understanding of perceptions of actors regarding their vulnerabilities and capacities.

Keywords Physical vulnerability · Social vulnerability · Risk assessment · Flash flood · East Attica · Greece

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1 Introduction

Threats by natural hazards are usually manifest through losses and are therefore negatively evaluated. They are the result of both the frequency and intensity of a hazardous event and the susceptibility of society and elements at risk. Therefore, the assessment of vulnerability requires an ability to identify and understand the exposure of elements at risk and—in a broader sense—of society to these hazards. An integrative vulnerability assessment is an essential step within risk management in order to plan and implement mitigation measures and management strategies.

Current approaches in vulnerability research are driven by a divide between social scientists and natural scientists, even if recently some attempts have been made to bridge this gap: apart from holistic frameworks resulting from interdisciplinary research projects such as MOVE (Birkmann et al. 2013) or ENSURE (Menoni et al. 2012), there are some approaches related to practical application and implementation available [e.g., Fuchs (2009) rooting in natural sciences and Renn (2008) in social sciences]. Whereas social scientists tend to view vulnerability as representing a set of socio-economic factors that determine the ability of society to cope with stress, to anticipate changes or to recover from the impact of hazards (cf. Wisner 2004; Birkmann 2006; Field et al. 2012), scientists often view vulnerability in terms of the degree of loss to an element at risk as a result of the impact of a hazard with a given frequency and magnitude (e.g., Fell et al. 2008; Papathoma-Köhle et al. 2011). So far, representatives from each discipline often define vulnerability in a way which fits to their individual disciplinary purposes. However, the different dimensions of vulnerability such as physical, social or economic vulnerability, although maybe differently defined, are connected to each other (Fuchs 2009; Papathoma-Köhle et al. 2011; Kappes et al. 2012a, b). Traditionally, the challenge of vulnerability refers to three different aspects of integration (cf. Fuchs et al. 2011):

- Integration of the components of vulnerability, which is related to the different characteristics most vulnerability studies consider such as exposure, susceptibility as well as coping and adaptive capacities and how to integrate these various components into an overall understanding, framework or model. Initially, in vulnerability research, the focus was on the internal side (coping capacity of people or systems) as well as on the external side of vulnerability [exposure of people to stress or perturbation and to societal structures people could not change; Chambers (1989)]. Subsequently, it was increasingly regarded as more important to focus on capacities of people to cope with and adapt to hazardous events and processes (Kuhlicke et al. 2011). Scientific approaches on the other hand typically focus on the susceptibility of physical elements at risk to natural processes (e.g., Fuchs et al. 2007; Totschnig and Fuchs 2013) in order to provide information necessary for operational risk analyses and technical mitigation. Through the rise of research on the consequences of climate change, another categorization gained relevance which includes the components of exposure, sensitivity and adaptive capacity and/or resilience (Turner II et al. 2003).
- Integration of methods for assessing vulnerability, which refers to different approaches used in vulnerability assessment and to what extent they are integrated for exploring vulnerability from different perspectives. The methodological repertoire is quite considerable in vulnerability science reaching from locally embedded research modes to highly advanced integrative, mostly GIS-based regional modelling approaches. On the one hand, a general difference can be made between rather participatory, inductive vulnerability assessments aiming at a better understanding of perceptions of actors

regarding their vulnerabilities and capacities in order to develop locally embedded adaptation and coping strategies. On the other hand, rather taxonomic, deductive vulnerability assessment can be carried out targeted at identifying, comparing and quantifying vulnerability of areas, groups or sectors by relying on different indicators and indices (Wisner 2006).

- Target dimension of vulnerability assessment, which refers to the different facets of vulnerability such as, for instance, whether an appraisal is focusing on economic consequences, the consequences for the built environment or on environmental or social vulnerabilities. Many vulnerability assessments based on economics or engineering sciences are concerned with the evaluation of monetary damages on assets, especially on buildings and their inventories (Fuchs et al. 2012). In contrast, social scientists are more concerned with the impacts on and coping and adaptation capacities of people, households and communities and the underlying root causes (e.g., Wisner et al. 2004). The challenge of integration hence relates to the question whether it is possible (or desirable) to consider and evaluate the interdependencies and interconnectedness among systems and components of vulnerability. By combining these different aspects, we present an integrative regional study on vulnerability to flash flood hazards in Greece. We will address key elements framing vulnerability, which are (1) exposure, (2) susceptibility and (3) societal response.

Flash floods are rapid surface water responses to rainfall from intense thunderstorms or a sudden release of water from a reservoir, which results in short lead time and a considerable potential for damage due to high flow velocities and thus high hazard intensities (Hong et al. 2012). Semi-arid regions with an episodic—often ungauged—drainage system are typically prone to flash floods, in particular if the local geology is characterized by loose sediments available for erosion or remobilization. Inundation occurs over normally dry land and is regularly associated with short-term, high-intensity rainfall of convective origin on a local scale (Borga et al. 2011). As a consequence, runoff rates often exceed those of other flood types due to the rapid response of the catchments to the rainfall event, modulated by high soil moisture and soil hydraulic properties (Borga et al. 2010). Barredo (2007) and Gaume et al. (2009) noted a seasonality effect on flash flood occurrence, with events in the Mediterranean region and the Southern European Alps (which includes regions in Spain, Greece, France, Italy and Slovenia) mostly occurring in autumn, and events in the Eastern Central Europe (Austria, Romania and Slovakia) commonly occurring in summer. This reveals a diversity of meteorological and hydrological triggers (Gaume et al. 2009), such as, e.g., small-scale convective systems during the summer period or larger-scale frontal rain (Reid 2003). In consistency with this effect of seasonality, the spatial extent and temporal duration of the events are generally reported to be smaller for the Central European floods compared to those occurring in the Mediterranean area (Marchi et al. 2010). Further, Montz and Gruntfest (2002) and Gaume et al. (2009) observed an increase of impacts of flash flood events even as the ability of forecasting and warning improved (Montz and Gruntfest 2002). This increase may be a result of a combination of dynamics underlying such extreme events and the exposure of assets and population in endangered areas (Calianno et al. 2013), even if some flash flood-prone areas may have experienced a decrease in population and assets (Bätzing 2002).

In Greece, such event type is usually resulting from high-intensity precipitation events of short duration in combination with deforestation and urbanization leading to a high sediment availability (Diakakis et al. 2012; Karagiorgos et al. 2013). Flash floods are described as being more destructive in the area of Attica as well as in the western part of

Greece due to the climatic, geomorphologic, vegetation and anthropogenic conditions (Llasat et al. 2010). The area was affected by several flash floods events in the past 20 years, especially in 1993, 1994, 2002 and 2005. The 1994 event (included an 11 h total rainfall duration) affected the whole Attica region with a probably of occurrence of 1/500 years (Lasda et al. 2010). The maximum total accumulated point rainfall was 131.2 mm with a 67.7 mm/h maximum intensity over time of concentration (Lagouvardos et al. 1996; Llasat et al. 2010). The event amounting to resulted in material damage € 13 million for commercial and industrial properties and € 1 million for residential properties (Mimikou and Koutsoyiannis 1995). Moreover, the 23–25 November 2005 event (maximum total accumulated point rainfall was 200 mm with a maximum intensity over time of concentration of 19 mm/h) caused in eastern Attica region high damages to commercial and residential properties as well as agricultural land (Llasat et al. 2010).

Our study has been carried out in the regional unit of East Attica (Fig. 1), which is a part of the Attica region located east of Athens in Greece. The study area extends from the municipality of Oropos in the North to the municipality of Lavreotiki in the South and is subdivided into the provinces of Marathon, Mesogia and Lavriotiki. The district covers an area of 1513 km^2 between sea level and 1109 m a.s.l. with a plain hilly relief and a population amounting to 502,348 inhabitants (Hellenic Statistical Authority 2011). The geological structure of East Attica is dominated by two main units (Alexakis 2011), (a) the crystalline basement (Paleozoic-Upper Cretareous) which is composed from metamorphic

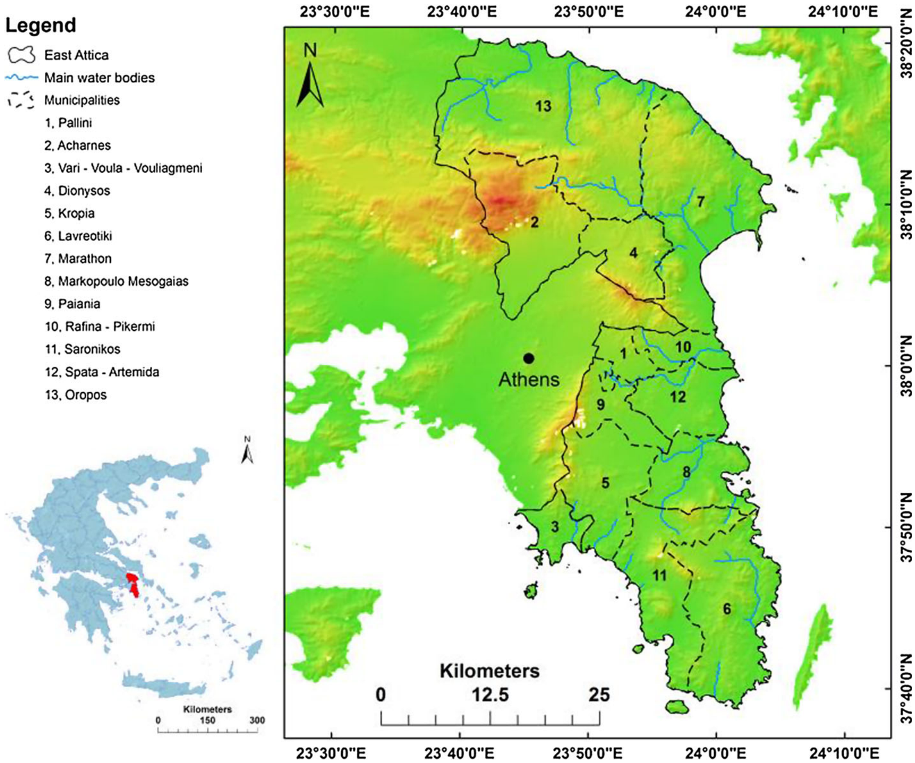

Fig. 1 Location of the study area in Greece

rocks (marbles, schists and phyllites) and (b) Neogene–Quaternary deposits consisting of clays, marls, conglomerates, ophiolite fragments, sandstones and other coarse and unconsolidated erosion-prone sediments. The climate of the area is typical Mediterranean with hot, dry summers and cool, wet winters, including a long arid period between April and September (Petropoulos et al. 2012). The land surface is mainly covered by sparse sclerophyllous vegetation, and some agricultural land at lower elevations. The higher altitudes are dominated by forest of different types as well as transitional woodland/scrubland vegetation.

The study area is characterized by extensive anthropogenic activities with settlements continuously growing. The economic development of this area is closely related to the construction of the international airport of Athens in 2001. In the period 1998–2010, the annual rate of increase of building development had been within a range of 5–30 % (Sapountzaki et al. 2011). As reported by Mantelas et al. (2010), the province of Mesogia has developed faster than any other area in Attica during the last 20 years. Specifically, the urban land cover increased from 60 km^2 in 1994, to 75 km^2 in 2000 and to 125 km^2 in 2007. In other words, while the urban cover grew by 25 % during 1994–2000, it grew by 66 % during 2000–2007.

In the subsequent sections, we will present our coupled approach to assess vulnerability in the test site.

2 Method

The assessment of vulnerability implies a quantitative valuation of the individual vulnerability components: elements at risk, their physical exposure and social characteristics as well as the underlying institutional settings responsible for exposure. In this work, the internal and external side of vulnerability was coupled. We studied the coping capacity of citizens affected by flash floods and their adaptation as well as the exposure and physical susceptibility of buildings at risk.

2.1 Physical vulnerability

Vulnerability functions can be used to empirically link the susceptibility of elements at risk to the magnitude of the impacting hazardous process (Fuchs et al. 2007) and are applied within integral risk management to quantitatively assess individual and collective risk. Vulnerability is conceptualized by a damage ratio between loss and the value of the exposed element at risk, facing spatial and temporal distributions of process intensities (e.g., flow depths, accumulation heights, flow velocities and pressures). While for mountain torrents, such functions have been increasingly reported during recent years (for an overview compare Papathoma-Köhle et al. (2011) and Totschnig et al. (2011)), a similar quantification is still outstanding for flash floods.

Within this study, the damage ratio was quantified using an economic approach by establishing a ratio between the loss and the reconstruction value of every individual element at risk exposed. In a second set of calculations, this value obtained for every individual building was attributed to the respective process intensities. The relation between damage ratio and process intensity was defined as vulnerability, following an engineering approach (Fuchs et al. 2007). Therefore, information on the elements at risk exposed in the test site was necessary, as well as data on the process intensities of the particular hazardous events. As a result, scatterplots were obtained linking process intensities to object vulnerability values. These data were analysed using regression approaches in order to deduce vulnerability functions which served as a proxy for the structural resistance of buildings with respect to flash floods in the catchment.

The characteristics of the buildings exposed were determined by the information included in the loss assessment reports collected by the Prefecture of East Attica. The characteristics delineated by the reports are the type of the building, the number of the floors, the area, construction materials used and, in some cases, the year of construction. Following suggestions by Keiler et al. (2006), buildings exposed were evaluated by assigning monetary values to them. These values (gross values) were based on the building size using an average value for individual part of a building: for residential buildings, an average value of 1000 €/m^2 for the main building envelope, 500 €/m^2 for the cellar and 300 €/m^2 for the household contents, was the basis for our analysis; these values are regularly used by Greek insurers if insurance premiums are to be computed (Kechri 2014, pers. comm.). According to the Greek building regulations (Greek Ministry for the Environment, Physical Planning and Public Works 1989), residential building refers to the structure or to parts of a structure used to provide a proper space for sleeping, body caring and cleaning, where inhabitants live permanently or temporarily. Household contents are usually defined as everything included in a house but not permanently installed, such as rugs, portable electric devices and standing bookshelves (USACE 1992).

As damage had only been reported qualitatively in the loss assessment reports received from the Prefecture of East Attica, for the building envelope the necessary quantitative values were calculated for each building using data given by the Earthquake Recovery Service of Greece (Greek Ministry of Infrastructure, Transport and Networks 2011). These monetary values included necessary reconstruction materials, taxes and salaries of the workforce, see Table 1. Damages referring to the household contents were calculated using the respective legal amendment (Greek Ministry for Health and Social Solidarity 2001, see

Table 1 Prices of repair work according to the 'Invoice for the calculation of necessary repair works in buildings affected by natural hazards (earthquake, forest fires, floods, landslides) and the respective housing assistance' (Greek Ministry of Infrastructure, Transport and Networks 2011)

Repair work	Unit of measurement	Cost (€)
Masonry reconstruction (25–50 cm thickness)	m^3	42
Masonry reconstruction with concrete bricks	m^3	15
Wall colouring	m^2	7
Wood floor reconstruction	m^2	40
Floor reconstruction with tiles	m^2	30
Exterior (main door) replacement	Piece	400
Interior door replacement	Piece	150
Balcony doors and windows	Piece	150
Balcony doors and windows with shutter	Piece	300
Heating system (repair or replacement)	Unit	1000
Electric Installation (repair or replacement)	Unit	800
Drainage installation (repair or replacement)	Unit	500
Plump installation (repair or replacement)	Unit	500

Table 2 Maximum damage compensation paid out by the administration referring to the household contents under the 'Specifications for the calculation of the financial support for families or people affected by natural hazards' values are given in Euros (Greek Ministry for Health and Social Solidarity 2001)

Size of residence	Family size (persons)																	
	1			2			3			4			5			6+		
	Maximum damage compensation																	
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
<50 m^2	1179	1887	2358	1415	2264	2830	1651	2641	3302	1887	3019	3773	2123	3396	4245	2358	3773	4717
50–80 m^2	1327	2123	2653	1592	2547	3184	1857	2972	3714	2123	3396	4245	2388	3821	4776	2653	4245	5306
>80 m^2	1474	2358	2948	1769	2830	3538	2064	3302	4127	2358	3773	4717	2653	4245	5306	2948	4717	5869

A, B and C refer to the quantitative distinguished degree of damages in the affected household

Table 2). These calculations were based on the number of residents within every accommodation unit, the size of the accommodation unit and the categorized degree of damage which was obtained from the loss assessment reports. As a result, the legally upper limit of compensation was included into our calculation for the overall loss.

As shown by Totschnig et al. (2011), information on the process intensity may be used to quantify the impact on an element at risk. The intensity of flash floods is generally quantified by a combination of flow velocity and flow height (the energy curve). Since data on flow velocity were not available, in our study, the assessment of the flash flood intensity was undertaken focusing on the water depth as a proxy using the event documentation of the eight events occurring during the period 1996–2006. This information had been extracted from the loss assessment reports on absolute water depths inside the houses, collected by the Prefecture of East Attica. The frequency of these events was 1/10 to 1/30 years. Moreover, based on the observation in European mountain regions that the cellar and ground floor are more susceptible to flooding than any other storey, a normalized relative intensity I_R has been used to test the sensitivity of the building height to vulnerability following the ideas presented by Totschnig et al. (2011). This relative intensity was computed from a ratio between the observed water depth I and the height of the affected building H (Eq. 1).

$$I_R = \frac{I}{H} \tag{1}$$

For the calculation of vulnerability functions, the process intensity and the degree of loss were assessed for every individual building. A nonlinear regression approach was used to obtain cumulative distribution functions following the computational requirements that (1) the depending variable—degree of loss—was defined in a both-sided confined interval [0,1]; and (2) the function increases steadily and monotonic within the interval of its explaining variable (which was intensity). Different vulnerability functions available in the literature (Totschnig et al. 2011; Totschnig and Fuchs 2013), such as Weibull, Frechet, Exponential and Logistic were tested within this study.

The root mean square error (RMSE, Eq. 2) was used for the differences between the values predicted by our model and the values actually observed. RMSE measures the overall agreement between observed and modelled events and indicates the absolute fit of a model to the data, as well as how close the observed data points are to the predicted values

Table 3 The values for the root mean square error (RMSE) for the different functions tested within this study

Function	RMSE			
	Absolute		Relative	
	Without cellar	With cellar	Without cellar	With cellar
Weibull	0.039	0.055	0.036	0.022
Exponential	0.041	–	0.038	0.067
Frechet no. 1	0.041	0.056	–	–
Frechet no. 2	0.041	0.056	–	–
Logistic	0.040	0.056	0.038	0.023

of the model. Lower values of RMSE indicate better fit, and if the model was perfect, RMSE would be zero. RMSE has non-negative values and no upper bound. The different functions were trained on the datasets, and the RMSE was obtained for each one of them. Finally, as Weibull obtained the smallest RMSE in our calculations, the function was chosen for the computation of vulnerability because it was found to represent the data sets best (see Table 3).

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(Q_i - \hat{Q}_i\right)^2}{n}} \qquad (2)$$

In Eq. (2) Q_i and $\hat{Q}_i$ are the observed and the modelled values at time i, with n being the total number of time intervals (Montesarchio et al. 2009).

In order to mirror the typical Greek building categories, the data were split into three groups according to a classification scheme (see Figs. 2, 3, 4). Class A contained buildings with columns (pilotis) as ground-level supporting structures which are characteristic for houses in highly urbanized areas of the country. Class B contained buildings without such pilotis but with enhanced ground plates; with residential use in the ground floor and—mainly—with cellar as a similar characteristic example of housing in urbanized areas of Greece. Category C contained buildings with non-enhanced ground plates, residential use in the ground floor but mainly without a cellar. Residential buildings in urban areas in Greece are commonly constructed by reinforced concrete (according to earthquake retrofitting principles) and bricks. Using data from the period between 1996 and 2006, a total

Fig. 2 Building category A with columns (pilotis) as ground-level supporting structures

Fig. 3 Building category B with enhanced ground plates and residential use in the ground floor and—mainly—with cellar typical for urbanized areas of Greece

Fig. 4 Building category C with non-enhanced ground plates and residential use in the ground floor

Table 4 Descriptive statistics of the study on social vulnerability

Community	*N*	Mean age (SD)	Gender		Homeowner	
			Male (%)	Female (%)	Yes (%)	No (%)
Nea Makri	24	39.6 (14.8)	51.35	48.65	86.11	13.89
Oropos	42	44 (13.6)	55.81	44.19	93.02	6.98
Rafina-Pikermi	25	35.3 (11.4)	45.95	54.05	81.08	18.92
Marathonas	23	38.4 (12.4)	53.85	46.15	74.36	25.64

of 114 buildings were analysed. In order to distinguish this dataset according to the exposure to flash floods, the criterion of cellar was additionally used.

2.2 Social vulnerability

The social vulnerability assessment was undertaken by means of empirical data collections which were conducted between the months May and June 2012 based on a door-to-door survey technique. The selection processes were based on flood victims. The total numbers of respondents were 114 flood victims distributed between four different study sites in the East Attica catchment. In Table 4, the descriptive statistic from the respondents is shown. The distributions between the respondents are very similar and balanced between the different areas.

Based on a literature review (Tapsell et al. 2002; Cutter et al. 2003; Fekete 2009; Felsenstein and Lichter 2014); we selected in total 11 variables (Table 5) to assess the social vulnerability of residents in East Attica. The variables mainly focus to the two aspects of (1) local embeddedness, such as family and friends living in the communities, members of local associations or local social networks and (2) socio-economic characteristics, such as employment rate or educational background, with particular focus on the consequences and impacts of the current social and economic crises in Greece. Main reason—to use these variables—is the capacity to cope with the impacts of flood events. The dependency on the age (elderly and children) shows a higher social vulnerability than others, because of their lack of mobility as well as low social status and power in the society. Further, the socio-economic structure of individuals or families, such as education, employment or income, also strongly influences the social vulnerability within the region. Financial savings as well as the lack of knowledge for implement and use individual mitigation measures show in general a positive correlation with low social vulnerability (Cutter et al. 2003; Fekete 2009). Further, risk perceptions in regard to flood risk management generally include a positive correlation with local (private) flood protection measures (Grothmann and Reusswig 2006; Lo 2013; Birkholz et al. 2014).

Table 5 Social vulnerability index used for flash flood risk management

Variable name	Impact: positive effects on social vulnerability (−) = high social vulnerability; negative effects on social vulnerability (+) = low social vulnerability
Local embeddedness and social networks (e.g., friends living in the village, trust in people, solidarity, member of local associations)	High local embeddedness (−)
Age	Elderly (+); children (+)
Occupation	Unemployed (+)
Household structures	Large families (+)
Education	Highly educated (−)
Disabled or non-self-sufficient persons	Disabled persons in household (+)
Risk awareness	High-risk awareness and understanding (−)
Risk experience	Risk experiences (−)
Impacts of economic crises	Income losses cause of financial and economic crises (+)
Residential property	Private ownership (−)
Financial savings	Yes (−)

3 Results

3.1 Physical vulnerability

A total of 114 buildings suffered from losses initiated by flash floods in the test site. A share of 64 buildings was classified as not having a cellar, approximately 70 % of them were with ground floor only (66 % of all buildings located in East Attica), more than 28 % with a second floor (24 % of all buildings located in East Attica) and almost 2 % were higher (10 % of all buildings located in East Attica). On the other hand, a total of 50 buildings were classified as having a cellar, almost 70 % of them were with ground floor only (43 % of all buildings located in East Attica), almost 30 % with a second floor (42 % of all buildings located in East Attica) and less than 2 % with a third floor or more (15 % of all buildings located in East Attica).

3.1.1 *Absolute vulnerability values*

In Fig. 5, the vulnerability relations for residential buildings with and without cellar are shown based on absolute flood intensities. The hazard intensity is plotted on the abscissa (x-axis) and grouped in steps of 0.5 metres, and the degree of loss is plotted on the ordinate

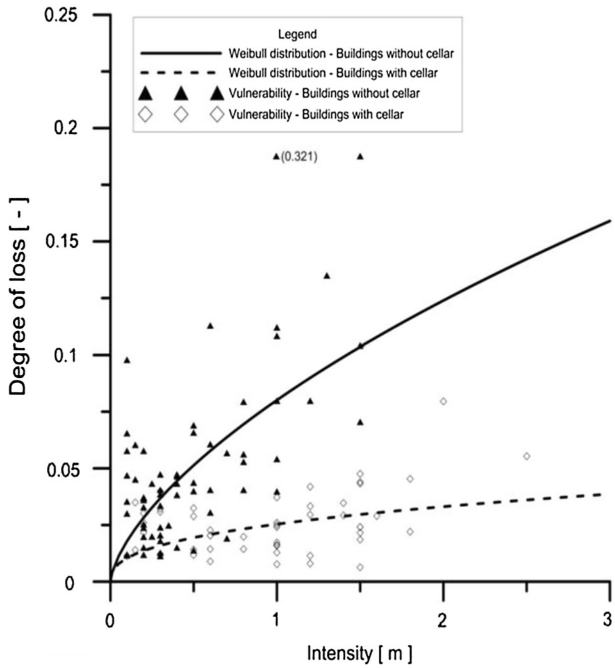

Fig. 5 Vulnerability relations for residential buildings with and without cellar based on absolute flood intensities. The *black triangles* show data for the vulnerability of buildings without cellar, the *white rhombi* show the data for the vulnerability of buildings with cellar. The *solid line* represents the Weibull distribution for the buildings without cellar, and the *dashed line* represents the Weibull distribution for the buildings with cellar

(y-axis). The distribution of the data according to process intensity classes is summarized in Fig. 6.

- Within the intensity class of 0–0.5 m, the spread of the vulnerability for the buildings without a cellar is from 0.011 to 0.097 with a mean vulnerability of 0.035. For the buildings with cellar, the spread of the vulnerability value is between 0.011 and 0.040 with a mean vulnerability of 0.024.
- Within the intensity class of >0.5–1.0 m, the spread of the vulnerability for the buildings without a cellar ranges from 0.019 to 0.321 with a mean vulnerability of 0.079. For the buildings with cellar, the spread of the vulnerability value is between 0.007 and 0.037 with a mean vulnerability of 0.018.
- Within the intensity class of >1.0–1.5 m, the spread of the vulnerability for the buildings without a cellar ranges from 0.070 to 0.187 with a mean vulnerability of 0.115. For the buildings with cellar, the spread of the vulnerability value is between 0.006 and 0.047 with a mean vulnerability of 0.027.
- Within the intensity class of >1.5–2.0 m, the spread of the vulnerability for the buildings with cellar is between 0.022 and 0.079 with a mean vulnerability of 0.043.
- Within the intensity class of >2.0–2.5 m, only one case was recorded for the buildings with cellar, with a vulnerability of 0.055.

The total loss of the buildings without cellar amounted to €307,884 (reconstruction and household values), with a range from €1174 to 10,533 and with individual vulnerabilities ranging from 0.011 to 0.321. The mean loss height equals €4,810 with a mean vulnerability of 0.052 per building without cellar.

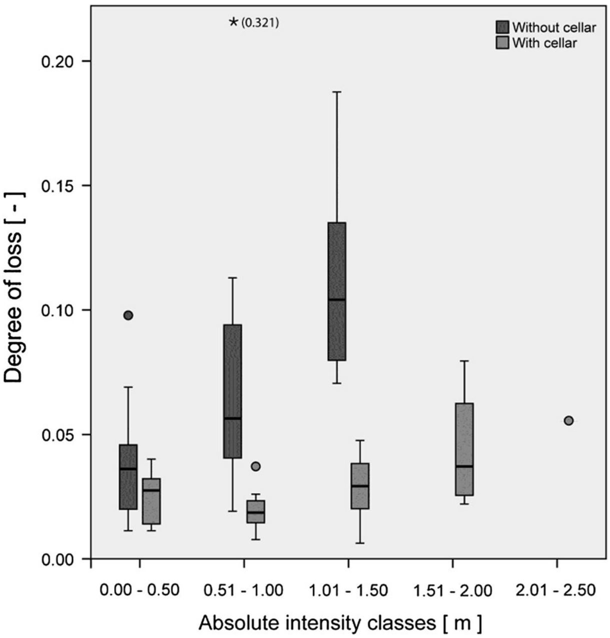

Fig. 6 *Box-plots* which highlight the range in the vulnerability values according to absolute process intensity classes (*dark grey* vulnerability of the buildings without cellar; *light grey* vulnerability of the buildings with cellar; *circle* mild outlier between 1.5 and 3 inter-quartile ranges; *asterisk* extreme outlier outside of 3 inter-quartile ranges)

In general, for the buildings without a cellar the results suggest a relatively sharp increase in vulnerability until a flood height of 0.5 m, and a successively flattening curve when the flood intensity becomes higher (see Fig. 5). The relationship between the process intensity x and the degree of loss y was found to fit best to a Weibull distribution with the parameters shown in Eq. (3).

$$V_{\text{abs.}} = 1 - e^{-0.307\left(\frac{x+7.104}{7.104}-1\right)^{0.664}} \tag{3}$$

Similarly, for the buildings with cellar, a gradual flattening is traceable once the process intensity becomes higher (see Fig. 5). The reconstruction values amounted to €210,410 with a range between €2113 and 7553 and with respective vulnerability values ranging from 0.006 to 0.079. The mean loss height equals € 4208 with a mean vulnerability of 0.025 per building with cellar. The relationship between the process intensity x and the degree of loss y was found to fit best to a Weibull distribution with the parameters shown in Eq. (4).

$$V_{\text{abs.}} = 1 - e^{-0.032\left(\frac{x+1.756}{1.756}-1\right)^{0.283}} \tag{4}$$

3.1.2 Relative vulnerability values

In Fig. 7, the vulnerability relations for residential buildings with and without cellar are shown based on relative flood intensities in order to take into account the different building heights. The process intensity normalized with the building height is plotted on the abscissa

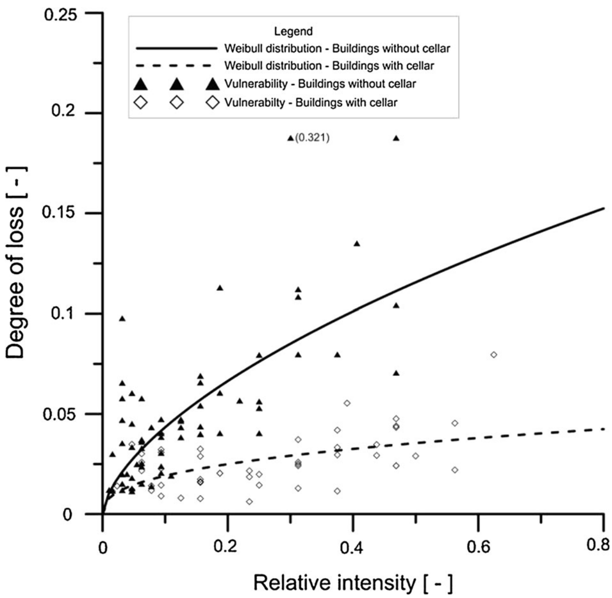

Fig. 7 Vulnerability relations for residential buildings with and without cellar based on relative flood intensities. The *black triangles* show data for the vulnerability of buildings without cellar; the *white rhombi* show the data for the vulnerability of buildings with cellar. The *solid line* represents the Weibull distribution for the buildings without cellar, and the *dashed line* represents the Weibull distribution for the buildings with cellar

(x-axis) and grouped in steps of 0.1, and the degree of loss is plotted on the ordinate (y-axis). This normalization was based on a quotient between the reported flood intensity (water depth) and the individual heights of the affected buildings. The relationship between the relative intensity x and the degree of loss y was found to fit best to a Weibull distribution with the parameters shown in Eq. (5) for the buildings without cellar and in Eq. (6) for the buildings with cellar.

$$V_{\text{rel.}} = 1 - e^{-0.826\left(\frac{x+10.153}{10.153}-1\right)^{0.633}} \tag{5}$$

$$V_{\text{rel.}} = 1 - e^{-0.112\left(\frac{x+9.189}{9.189}-1\right)^{0.389}} \tag{6}$$

The distribution of the data according to the process intensity classes is summarized in Fig. 8.

- Within the relative intensity class of 0–0.1, the spread of the vulnerability for the buildings without a cellar is from 0.0113 to 0.0656 with a mean vulnerability of 0.0305. For the buildings with cellar, the statistical spread of the vulnerability value is between 0.0090 and 0.040 with a mean vulnerability of 0.0217.
- Within the relative intensity class of >0.1–0.2, the spread of the vulnerability for the buildings without a cellar ranges from 0.0191 to 0.1129 with a mean vulnerability of 0.0515. For the buildings with cellar, the spread of the vulnerability value is between 0.0077 and 0.0325 with a mean vulnerability of 0.0186.

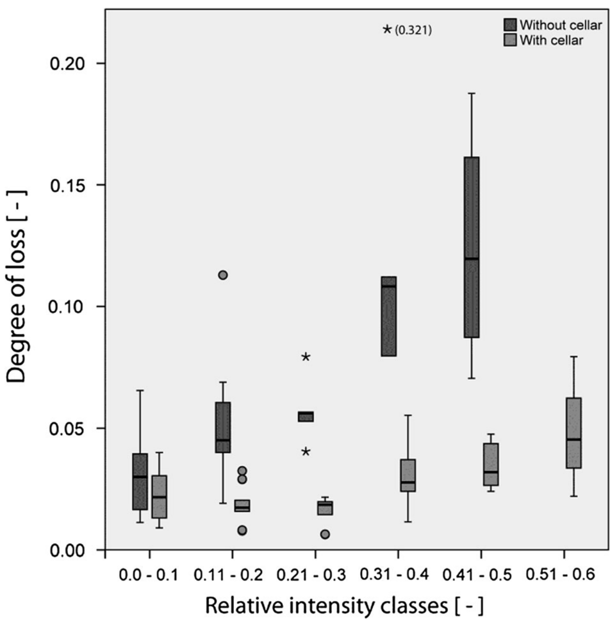

Fig. 8 *Box-plots* which highlight the range in the vulnerability values according to relative process intensity classes (*dark grey* vulnerability of the buildings without cellar; *light grey* vulnerability of the buildings with cellar; *circle* mild outlier between 1.5 and 3 inter-quartile ranges; *asterisk* extreme outlier outside of 3 inter-quartile ranges)

- Within the relative intensity class of >0.2–0.3, the spread of the vulnerability for the buildings without a cellar ranges from 0.0405 to 0.0794 with a mean vulnerability of 0.0571. For the buildings with cellar, the spread of the vulnerability value is between 0.0063 and 0.0217 with a mean vulnerability of 0.0162.
- Within the relative intensity class of >0.3–0.4, the spread of the vulnerability for the buildings without a cellar ranges from 0.0798 to 0.3210 with a mean vulnerability of 0.1402. For the buildings with cellar, the spread of the vulnerability value is between 0.0115 and 0.0553 with a mean vulnerability of 0.0297.
- Within the relative intensity class of >0.4–0.5, the spread of the vulnerability for the buildings without a cellar ranges from 0.0705 to 0.1876 with a mean vulnerability of 0.1243. For the buildings with cellar, the spread of the vulnerability value is between 0.0241 and 0.0476 with a mean vulnerability of 0.0345.
- Within the relative intensity class of >0.5–0.6, the spread of the vulnerability for the buildings with cellar is between 0.0220 and 0.0795 with a mean vulnerability of 0.0490.

3.1.3 Comparison between absolute and relative vulnerability

In Table 6, the parameters of the obtained Weibull equations for buildings without cellar and buildings with cellar are summarized for the underlying absolute and relative intensities. Additionally, the values for the root mean square error (RMSE) are indicated. Moreover, the amount of buildings analysed is given according to the three categories of construction A–C, see Figs. 2, 3, 4. The lower the RMSE the better is the vulnerability function derived in predicting vulnerability resulting from flash flood hazards in the same region. The RMSE is 0.039 for the buildings without cellar and 0.055 for the buildings with cellar for absolute values, and 0.036 for the buildings without cellar and 0.022 for the buildings with cellar for relative values. As for both absolute and relative intensities these values are close to zero, we suggest that both methods may be equally applied.

Table 6 Parameters of the obtained Weibull coefficients for buildings without cellar and buildings with cellar, and the amount of buildings analysed according to the three categories of construction A–C are given for relative and absolute process intensities

	Absolute intensity		Relative intensity	
	Buildings without cellar	Buildings with cellar	Buildings without cellar	Buildings with cellar
Weibull distribution coefficients				
a	−0.307	−0.032	−0.826	−0.112
b	7.104	1.756	10.153	9.189
c	0.664	0.283	0.633	0.389
RMSE	0.039	0.055	0.036	0.022
Building categories				
A	3	2	3	2
B	15	39	15	39
C	46	9	46	9

An analysis of the building categories A–C with respect to the degree of loss resulted in considerable differences (see Table 7).

- Buildings with pilotis (category A) were the least susceptible. The degree of loss ranged from 0.0113 to 0.0238 with a mean value of 0.0159 for the buildings without cellar and from 0.0063 to 0.0080 with a mean value of 0.0071 for the buildings with cellar.
- Buildings with enhanced ground plates (category B) and without cellar were less susceptible than buildings of category C without enhanced ground plates and without cellar. The degree of loss ranged from 0.0120 to 0.0798 and a mean value of 0.0422 (category B) and for category C, the degree of loss ranged from 0.0116 to 0.3210 and a mean value of 0.0585.
- Buildings without enhanced ground plates (category C) and with cellar were less susceptible than buildings of category B with enhanced ground plates. The degree of loss ranged from 0.0090 to 0.0433 and a mean vulnerability value of 0.0248 (category C) following category B with a degree of loss from 0.0077 to 0.0795 and a mean value of 0.0271.

3.2 Social vulnerability

The assessment of social vulnerability resulted in particular insights in local integration, household structures, self-concern and socio-economic structures which will be valuable for further future couple vulnerability evaluations.

The local integration is presented by a low degree of integration or embeddedness in the local community. This goes in the line with the low degree of solidarity [mean = 2.54; and a standard deviation of 1.34, respondents were asked to judge their perception on a 5-point scale; range from 1 (minimum) to 5 (maximum)] and trust (only 39.5 % answered with generally with yes) between the neighbours. Further, the result showed a low interest of engagement in the communities and strengthened the aspect of social isolation. The respondents showed no high interest in participating in local association groups (87.3 % answered with no). However, these results are totally in contradiction with the mean length of residency (mean = 34.85) of each respondents. The data showed a low degree of movement or change of residence from the respondents. Additionally, the household structures are an important factor influencing the construction and assessment of social vulnerability in the region. In particular, these variables play an important role during and after a flood event. In general, the respondents show an average household of 3.88 (mean value) people. Disabled or non-self-sufficient persons play minor impact within their decision process in the respondents, because only 3.8 % respondent householders answered with yes. Further, the sample shows a low age distribution (mean = 38.65) between the interviewee respondents. If data were considered, more than 7.6 % are 65 and older,

Table 7 Absolute vulnerability (min, max and mean) values according to the different building types

	No cellar			Cellar		
	Min	Max	Mean	Min	Max	Mean
A	0.0113	0.0238	0.0159	0.0063	0.0080	0.0071
B	0.0120	0.0798	0.0422	0.0077	0.0795	0.0271
C	0.0116	0.3210	0.0585	0.0090	0.0433	0.0248

whereabouts 3.16 % are very old (75 years and older). In summary, the potential of highly affected population groups (very young and old people) is more than 17.1 %. Additionally, the socio-economic structure showed very homogenous results. First indicator the ownership structure shows a high degree of private properties within the respondents. More than 82.8 % of the interviewees indicate as private owner of the house, where they life. A second indicator refers to the consequences from the financial and economic crises. In particular, the economic crises had a massive negative impact to the householders' income with the side effect of no investments in local protection measures. More than 85.8 % of the sample answered that they were not succeed to manage any savings or investments for their property. Moreover, the questionnaires show that the household income has problems to satisfy the family's needs (mean = 1.8, with a standard deviation of 1.01; where 1 is insufficient and sufficient is 5), where almost 95 % of the responded are employed. In referring the risk perception of the sample showed a high degree of concerns for the village, in contrast to the results for individual life and their property (Fig. 9).

4 Discussion

Focusing on physical vulnerability, an empirical relation between the process intensity and the degree of loss was established for exposed buildings. Thus, the proposed vulnerability function may be used in operational risk analyses for flash flood hazards in Mediterranean countries, particularly since the approach is suitable for a spatially explicit valuation within a GIS environment. The results were surprisingly low compared to other flood hazards (e.g., Fuchs et al. 2007; Apel et al. 2009; Totschnig and Fuchs 2013), which may be a result of the specific hazard characteristics in combination with the building design principles in Greece. These are apart from local construction preferences also a result of the strong anti-seismic regulations enacted in 1960 for an enhanced earthquake retrofitting, revised in 1985, 2000 and 2003 and providing one of the strictest earthquake design codes worldwide (Sarris et al., 2009). As such, the vulnerability functions are comparable to those reported

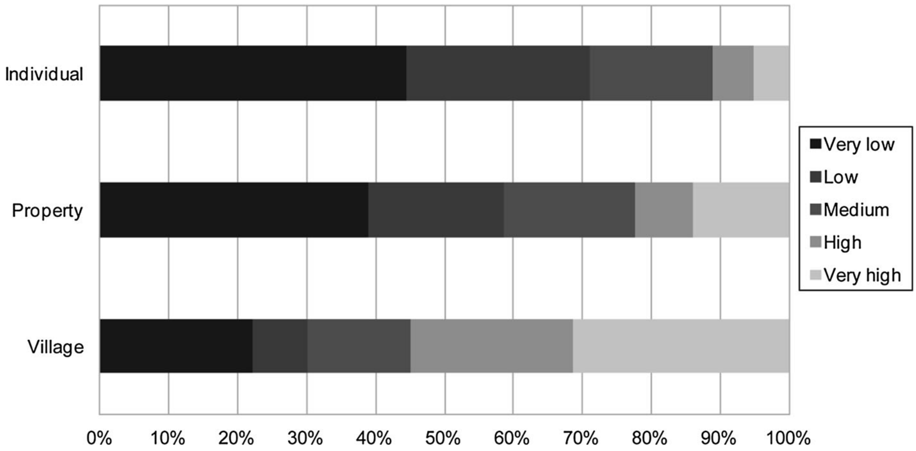

Fig. 9 Risk perception of flash flood hazards in the East Attica catchment. The values are shown from very low (=*black*) to very high (=*light grey*)

from other earthquake-prone regions with strong building codes, such as, e.g., Taiwan (Lo et al. 2012).

Residential buildings in East Attica are typically constructed with reinforced concrete and are often tiled in the ground floor, which makes them also waterproof. In contrast, residential buildings in Austria (Totschnig et al. 2011) and Germany (Apel et al. 2009) follow a different construction and design principle, which makes them more vulnerable to flooding. Moreover, in particular for the German buildings, a considerable part of the loss results from the flood duration apart from the water level inside the buildings (Kreibich et al. 2009). In contrast, the study of Totschnig et al. (2011) highlighted the importance of impact pressure as a result from a combination of flow height and flow velocity. Moreover, different methods were used in the reported studies (Apel et al. 2009; Kreibich et al. 2009; Totschnig et al. 2011) to obtain the vulnerability functions, which may also lead to different shapes of the damage curves.

Besides, the results for absolute hazard intensities have shown that a clear difference exists between the buildings with cellar—with very low vulnerability values—and the buildings without cellar with higher vulnerability values. This obvious contradiction may also be attributed to the specific interior design since the service connection for electricity and gas are usually located in the ground floor which would results in generally lower vulnerability values compared to Central Europe. Similarly, buildings of category B with enhanced ground plates were more vulnerable than those of category C without enhanced ground plates. One explanation is in the building design since the susceptible building openings are in the same height than the terrain surface (see Fig. 3), which may be more difficult to defence against the impacting hazard than the classical light wells used for category C buildings with cellar. Furthermore, in the test site, a large number of buildings were without heating system because of the climatic conditions of the area, which in turn significantly reduces the values exposed in the cellar. Finally, a considerable amount of buildings is only used during the summer months, which may again result in reduced value exposure compared to a year-round utilization. In addition, the legally upper limit of compensation was included in our calculations for the damages referring to the household contents. Therefore, lower vulnerability values may also be interpreted in terms of an economic maximum vulnerability from a governmental perspective, and real losses (for the content) may be higher than indicated in our set of calculation. To give an example, in European mountain regions, it is a standard procedure in insurance business to add a share of 20 % to the building values if the building content is not insured by own policies to mirror the average content value accordingly (Fuchs 2009).

In the second set of calculation, a normalization of the process intensity was undertaken, assuming that the flow depth will never exceed the building height. The results showed a slightly smaller RMSE which theoretically means a better predictive capacity of the relative model. In practice, the differences were so small that no general conclusion of a better applicability of the model should be drawn. It has been reported by Totschnig and Fuchs (2013) that the use of absolute vulnerability functions will lead to an overestimation for high buildings and an underestimation for small buildings, however, since the vulnerability values in East Attica were generally atypically small in comparison with other vulnerability functions (e.g., Apel et al. 2009; Papathoma-Köhle et al. 2011; Totschnig and Fuchs 2013), this aspect may be neglected. In turn, the additional variable of the relative model (building height) may result in better statistical measures of the magnitude of a varying quantity (degree of loss), but this may only be valid if more data on losses will become available. Another drawback of the relative intensity is the missing communicative possibility if such curves are presented to, e.g., decision-makers and other non-expert stakeholders. Therefore, it may be more appropriate to rely on the presentation of absolute figures.

In Table 8, the social vulnerability of the East Attica region is summarized. In overall, the respondents show a low social vulnerability, because of high employment rate, education level, risk perception, private ownership structure and age. In general, communities prone to flash flooding show a higher social vulnerability (de Marchi et al. 2007; Hopkins and Warburton 2014) compared to the East Attica region. Main reason was the socio-economic structure within the communities in East Attica, where in England or Italy often flash floods areas show a higher number of households with person in need (people older than 65 years or disabled) or higher number of people without an occupation (because of higher number of retired people or housewives). The sample in this study demonstrated a high private ownership structure, which is comparable with all Southern European countries. Private property plays a much higher role in Greece compared to European countries (such as Austria or Germany), because lack of social housing, high regulation at rent market and lack of trust to national state (Nguyen and Shlomo 2011). Further, the socio-economic data showed 'relative' high values, because of various developments in the past, such as the Olympic Games in 2004 and the proximity to the capital. During the economic growth (1990s–2000s), East Attica heavily gained from the economic growth in Greece, because of various infrastructure developments (Sapountzaki et al. 2011) in contrast to other Greek regions. However, the lack of local integration is a result of rapid developed in the past few years as the region show a classical suburbanization process from Athens (Morelli et al. 2014; Sapountzaki et al. 2011). This can have a negative impact in particular in the warning, mitigation and recovery phase. On the other hand, the sampling demonstrated a high-risk perception, which is a result from the recent flood history and frequency in the region because the catchment had continuously flood events in the past 20 years.

In general, flash flood victims show a lower risk perception in compare to river floods, because of the 'rareness' of such events (Gruntfest and Handmer 2001; Creutin and Borga

Table 8 Social vulnerability assessment for the East Attica catchment

Variable name	Impact: positive effects on social vulnerability (−) = high social vulnerability; negative effects on social vulnerability (+) = low social vulnerability
Local integration and social networks (e.g., friends living in the village, trust in people, solidarity, member of local associations)	(+)
Age	(−)
Occupation	(−)
Household structures	(−)
Education	(−)
Disabled or non-self-sufficient persons	(−)
Risk awareness	(−)
Risk experience	(−)
Impacts of economic crises	(+)
Residential property	(−)
Financial savings	(+)

2003) and there small (local) diffusion (Merz and Blöschl 2004). Further, flash floods often occur in rural areas were few people were affected and cannot get the same level of awareness at national level like large river floods (Kundzewicz et al. 1999). Therefore, it is difficult to motivate communities in flash floods prone areas to undertake precautionary measures (Montz and Gruntfest 2002), also because these types of floods are often too small to release an impact and trigger in the society (Burningham et al. 2008). Often, these types of flood processes produce a wrong 'security' feeling within the society (Wachinger et al. 2010; Scolobig et al. 2012; Hopkins and Warburton 2014). The results from East Attica showed another answer in comparison with other flash floods studies, such as recent work published by Hopkins and Warburton (2014). For example, more than 83.4 % of the interviewee disagreed that the last flash flood events were only a one or two-off event and will not happen again in the future. However, this high-risk perception could not increase the preparedness in the community; more than 50 % of the sample showed a very low/low level of individual preparedness. One reason can be found in the lack of trust in the public administration in Greece in contrast to other studies, such as de Marchi et al. (2007). Therefore, the response of the society to this high-risk perception and awareness is very limited, where we observed low expectations for the physical impacts of future flood events for individuals and their property. Consistent with previous studies (Scolobig et al. 2012), even if the frequency (and magnitude) of flash flood events may increase, a considerable low-risk awareness of exposed residents is reported, which is usually considered among the main causes of their low preparedness, which in turns generates inadequate response to natural disasters (Wachinger et al. 2010). One reason has been the 'small' impacts of these flood events towards the local communities (general flood return period was estimated 1/10 to 1/30 years). Mileti and O'Brien (1992) described this as: 'if in the past the event did not hit me negatively, I will escape also negative consequences of future events' (1992: 53). This limited concern about flash flood risk as a result from a lack of knowledge of people inhabiting flash flood-prone areas, together with the often missing early warning systems, the complicated and plethoric but insufficient systems of spatial planning and land use policy may additionally foster these disinterest. Moreover, in the studied Greek case, further social, cultural and economic factors due to the economic crisis of the last years may amplify this behaviour. Also, the financial and economic crises had a considerable impact to the household income with the impact that private householders cannot undertake individual flood protection measures.

5 Conclusions

Taking the case study of East Attica, Greece, as an example, we conducted a vulnerability assessment for elements at risk and communities exposed to flash flood hazards. The results demonstrate low values for the physical vulnerability as a result of the specific hazard characteristics in combination with the building design principles in Greece. Additionally, social vulnerability reported low as a result of the housing developments in the past 20 years in the region. Moreover, results show some degree of correlation between the two types of vulnerability analysed. To give an example, if physical vulnerability will change in the future with more severe events, the disposable and discretionary income of the affected citizens will change resulting changes to the social vulnerability of the area.

By analysing both physical and social vulnerability, an attempt was made to bridge the gap between scholars from sciences and humanities, and to integrate the results of the analysis into the broader vulnerability context. The empirical research presented in this paper stresses that there are several factors as well as interactions shape vulnerability in a dynamic concept. For example, the interdependencies of hazard parameters like flood frequency or duration, which influence the perception of the society and the impact of the hazard (Fekete 2010). As such this study refers to the different facets of vulnerability, as the economic and engineering evaluation of monetary damage is combined with a social impact assessment and an evaluation of adaptive capacities of people, households and communities. Moreover, and focusing on the challenges within the test site, the combination of different perspectives of physical and social vulnerability will probably lead to a better understanding of perceptions of actors regarding their vulnerabilities and capacities in order to develop locally embedded coping strategies developing alternative flood risk management. The assessment of physical vulnerability can provide an important tool in the hands of stakeholders for planning strategies in the future changes of the frequency and magnitude of hazardous events while social vulnerability assessment will help policy makers to implement strategies and operations in a way of place-specific local variability.

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