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Regional prioritisation of flood risk in mountainous areas

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Abstract

A regional analysis of flood risk was carried out in the mountainous area surrounding the city of Bogotá (Colombia). Vulnerability at regional level was assessed on the basis of a principal component analysis carried out with variables recognised in literature to contribute to vulnerability; using watersheds as the unit of analysis. The area exposed was obtained from a simplified flood analysis at regional level to provide a mask where vulnerability variables were extracted. The vulnerability indicator obtained from the principal component analysis was combined with an existing susceptibility indicator, thus providing an index that allows the watersheds to be prioritised in support of flood risk management at regional level. Results show that the components of vulnerability can be expressed in terms of four constituent indicators; socio-economic fragility, which is composed of demography and lack of well-being; lack of resilience, which is composed of education, preparedness and response capacity, rescue capacity, social cohesion and participation; and physical exposure is composed of exposed infrastructure and exposed population. A sensitivity analysis shows that the classification of vulnerability is robust for watersheds with low and high values of the vulnerability indicator, while some watersheds with intermediate values of the indicator are sensitive to shifting between medium and high vulnerability. The complex interaction between vulnerability and hazard is evidenced in the case study. Environmental degradation in vulnerable watersheds shows the influence that vulnerability exerts on hazard and vice versa, thus establishing a cycle that builds up risk conditions.

1 Introduction

Effective disaster risk reduction requires a comprehensive assessment of hazard and vulnerability. Flood risk represents the probability of negative consequences due to floods and emerges from the convolution of flood hazard and flood vulnerability

(Schanze et al., 2006). Assessing flood risk can be carried out at national, regional or local level (IWR, 2011), with the regional scale aiming at contributing to regional flood risk management policy and planning. Regional approaches vary widely, including hydrodynamic model-based hazard analyses with damage estimations (Liu et al., 2014; Su and Kang, 2005) as well as indicator-based analyses (Chen et al., 2014; Safaripour et al., 2012; Greiving, 2006), with the latter being less data-demanding. A common approach is to obtain grades (e.g. high, medium and low) for the risk categories that allow prioritisation or ranking of areas for implementation of flood risk management measures such as flood warning systems and guiding preparations for disaster prevention and response (Chen et al., 2014).

A risk analysis consists of an assessment of the hazard as well as an analysis of the elements at risk. These two aspects are linked via damage functions or loss models, which quantitatively describe how hazard characteristics affect specific elements at risk. This kind of damage or loss modelling typically provides an estimate of the expected monetary losses (Seifert et al., 2009). However, more holistic approaches go further than including just physical vulnerability and incorporate social, economic, cultural and educational aspects, which are in most cases the cause of the potential physical damage (Cardona, 2003).

As important as the understanding of the hazard, the knowledge of the social system and its vulnerabilities is a key element of risk, and determines the social response to floods (Barroca et al., 2006). Birkmann (2006) suggests that indicators and indices can be used to measure vulnerability from a comprehensive and multidisciplinary perspective, capturing both direct physical impacts (exposure and susceptibility), and indirect impacts (socio-economic fragility and lack of resilience). The importance of indicators is rooted in their potential use for risk management since they constitute useful tools for identifying and monitoring vulnerability over time and space, for developing an improved understanding of the processes underlying vulnerability, for developing and prioritising strategies to reduce vulnerability, and for determining the

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effectiveness of those strategies (Rygel et al., 2006). However, developing, testing and implementing indicators to capture the complexity of vulnerability remains a challenge.

The use of indices for vulnerability assessment has been adopted by several authors, for example, Balica et al. (2012) describe the use of a Flood Vulnerability Index (FVI), an indicator-based methodology that aims to identify hotspots related to flood events in different regions of the world. Müller et al. (2011) used indicators derived from geodata and census data to analyse the vulnerability to floods in a dense urban setting in Chile. A similar approach was followed by Barroca et al. (2006), organising the choice of vulnerability indicators and the integration from the point of view of various stakeholders into a software tool. Cutter et al. (2003) constructed an index of social vulnerability to environmental hazards at county-level for the United States. However, several aspects of the development of these indicators continue to demand research efforts, including: the selection of appropriate variables that are capable of representing the sources of vulnerability in the specific study area; the determination of the importance of each indicator; the availability of data to analyse and assess the indicators; the limitations in the scale of the analysis (geographic unit and timeframe); and the validation of the results (Müller et al., 2011). Furthermore, the complex interrelations between hazard and vulnerability, which are mutually conditioning (Cardona, 2003), constitute a key aspect in the comprehension of risk.

Vulnerability is closely tied to natural and man made environmental degradation at urban and rural levels (Cardona, 2003), while at the same time the intensity or recurrence of flood hazard events can be partly determined by environmental degradation and human intervention in natural ecosystems (Cardona et al., 2012). This implies that human actions on the environment determine the construction of risk, influencing the exposure and vulnerability as well as enhancing or reducing hazard, or even creating new hazards.

The complex interaction between hazard and vulnerability is explored in this paper in the context of small watersheds where human-environment interactions that determine risk levels take place in a limited area. The mountainous environment and the

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particular sensitivity to anthropic intervention of flash flood prone watersheds provide an ideal scenario to study the dynamics of risk conditions in the urban environment. Unplanned urbanisation characterised by a lack of adequate infrastructure and socio-economic issues (both contributors to vulnerability), may result in severe environmental degradation, which increases the intensity of natural hazards (UNISDR, 2004). The consequence of the interaction between hazard and vulnerability in the context of small watersheds is that those at risk of flooding themselves play a crucial role in the processes that enhance hazard.

This paper aims at the prioritisation of watersheds, which can be interpreted as a proxy for flood risk assessment, thus providing guidelines for the managing of those risks. A key factor is the determining of flood exposure at the regional level, which provides the areas where vulnerability is studied. Flood-prone areas are generally obtained through hydrologic and hydraulic modelling. These can be expensive and time consuming, particularly when large areas have to be modelled. Moreover, these require information that may not readily be available for all areas (Degiorgis et al., 2012). Flood hazard maps are therefore usually only available for limited areas. This creates difficulties when a regional assessment is needed. To overcome this challenge a combination of simplified existing methods is proposed in order to obtain the outline of the areas potentially exposed to floods. Vulnerability is then assessed through application of an indicator system that considers social, economic and physical aspects that are derived from the available data in the study area. This is subsequently combined with a flash flood susceptibility indicator based on morphometry and land cover (Rogelis and Werner, 2013). The resulting priority index reflects the watersheds with the highest damage potential that require detailed risk studies to establish appropriate flood risk management strategies.

The paper is structured as follows. Section 2 reviews the conceptual definition of vulnerability as the foundation of the paper. Subsequently, Sect. 3 describes the study area, and the data and methodology used; to delineate areas susceptible to flooding; to chose indicators and carry out the principal component analysis; to carry out the sensitivity analysis of the vulnerability indicator; to create categories of recorded damage in the study area; and to prioritise the watersheds. Section 4 presents the exposure areas obtained through the simplified methods; the results of the principal component analysis in terms of a socio-economic fragility indicator, a lack of resilience indicator and a physical exposure indicator; the overall vulnerability indicator obtained from the combination of the socio-economic fragility, lack of resilience and physical exposure indicators; the sensitivity analysis of the vulnerability indicator; and the prioritization of watersheds according to the qualitative risk indicator and comparison with damage records. Section 5 section interprets the results of the exposure area delineation, the representativeness and relative importance of the indicators obtained from the principal component analysis; the sensitivity of the vulnerability indicator; and the interrelations between susceptibility and vulnerability in the prioritisation indicator. The conclusions are summarised in Sect. 6.

2 Conceptualization of vulnerability

Several concepts of vulnerability can be identified, and there is not a universal definition of this term (Thieken et al., 2006; Birkmann, 2006). The definition of vulnerability depends on the type of study, on the results required, on the kind of hazard (flash-flood or slow evolving-flood) on the spatial and temporal scale of study, on the characteristics of the study area, and on the temporality (prevention, crisis, post crisis) (Barroca et al., 2006). Cutter et al. (2003) indicate that vulnerability to environmental hazards means the potential for loss. Jha et al. (2012) see vulnerability as the degree to which a system (in this case, people or assets) is susceptible to, or unable to cope with the adverse effects of natural disasters. It is a function of the character, magnitude and rate of hazard to which a system is exposed, the sensitivity or degree to which a system is affected adversely or beneficially, and its adaptive capacity (the ability of a system to adjust to changes, moderate potential damages, take advantage of opportunities or cope with the consequences). Cardona et al. (2012)

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state that vulnerability refers to the propensity of elements such as human beings, their livelihoods, and assets to suffer adverse effects when exposed to hazard events. It is related to the predisposition, susceptibility, fragility, weakness, and lack of capacity of the elements exposed. The International Strategy for Disaster Reduction (UN/ISDR) sees 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). The United Nations Development Programme (UNDP) in contrast defines vulnerability as: "A human condition or process resulting from physical, social, economic and environmental factors, which determine the likelihood and scale of damage from the impact of a given hazard" (UNDP, 2004). Taubenböck et al. (2008) define vulnerability as the condition determined by physical, demographic, social, economic, environmental and political factors or processes that increase the susceptibility of a community to the impact of hazards.

Birkmann (2006) distinguishes at least six different schools of thinking regarding the conceptual and analytical frameworks on how to systematise vulnerability. In these, the concept of exposure and its relation with vulnerability, the inclusion of the coping capacity as part of vulnerability, the differentiation between hazard dependent and hazard independent characteristics of vulnerability play an important role. For example, Merz et al. (2007) conceptualise vulnerability as composed of two elements: exposure (or damage potential) and (loss) susceptibility. Bohle (2001) explains that vulnerability deals on the one hand with features and characteristics linked to capacities to anticipate and cope with the impact of a hazard, and on the other, with the exposure to risks and shocks. Thus, vulnerability is the interrelation of the exposure and the susceptibility as stressor of the system with the coping capacity as the potential of the system to decrease the impact of the hazard. The internal dimension of vulnerability refers to defencelessness and insecurity, or conversely to the capacity to anticipate, cope with, resist and recover from the impacts of a hazard (Birkmann, 2006). The external dimension involves exposure to risks and shocks. The latter is mainly dependent on

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the geographical location or exposure. This term is defined by Su and Kang (2005) as the human activities affected by the hazardous event.

Several authors consider that vulnerability should not be limited to the estimation of the direct impacts of a hazardous event, meaning that vulnerability can also take into account the coping capacity and resilience of the potentially affected society (Birkmann, 2006). Authors such as Vogel and O'Brien (2004) as cited by Birkmann (2006) stress the fact that vulnerability is; multi-dimensional and differential (varies across physical space and among and within social groups); scale dependent (with regard to time, space and units of analysis such as individual, household, region, system); and dynamic (the characteristics and driving forces of vulnerability change over time).

For the purpose of this study the exposure of a given location is considered primarily as a feature of the hazard, as proposed by Birkmann (2006). The degree of exposure of a specific unit e.g. a critical infrastructure or the number of houses in the hazard-prone areas are a part of exposure that characterises the spatial dimension of vulnerability. Thus exposure is partially a characteristic of vulnerability (Birkmann, 2006), and is defined as people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses (UNISDR, 2009). Vulnerability is defined as an internal risk factor of the subject or system that is exposed to a hazard and corresponds to its intrinsic predisposition to be affected, or to be susceptible to damage (Cardona, 2003). Hence, if population and economic resources were not located in (exposed to) potentially dangerous settings, the problem of disaster risk would not exist. To be vulnerable to an extreme event, it is necessary to also be exposed (Cardona et al., 2012).

The approach to vulnerability assessment that is used in this study corresponds to the holistic approach proposed by Cardona (2001), where vulnerability consists of exposed elements that take into account several dimensions or aspects of vulnerability; physical exposure and susceptibility, which is designated as hard risk and viewed as being hazard dependent; fragility of the socio-economic system, which is viewed as soft

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risk and is non hazard dependent; and lack of resilience to cope and recover, which is also defined as soft risk and is non hazard dependent.

3 Methods and data

3.1 Study area

Bogotá is the capital city of Colombia with 7 million inhabitants and an urban area of approximately 385 km^2. The city is located on a plateau at an elevation of 2640 m a.s.l. and is surrounded by mountains from where several creeks drain to the Tunjuelo, Fucha and Juan Amarillo rivers. These rivers flow towards the Bogotá River. Precipitation in the city is characterised by a bimodal regime with mean annual precipitation ranging from 600 to 1200 mm (Bernal et al., 2007).

Despite its economic output and growing character as a global city, Bogotá suffers from social and economic inequalities, lack of affordable housing, and overcrowding. Statistics indicate that there has been a significant growth in the population, which also demonstrates the process of urban immigration that the whole country is suffering not only due to industrialization processes, but also due to violence and poverty. This disorganised urbanisation process has pushed informal settlers to build their homes in highly unstable zones and areas that can be subjected to inundation. Eighteen percent of the urban area has been occupied by informal constructions, housing almost 1 400 000 persons. This is some 22 % of the urban population, corresponding to some 3 700 000 dwellings (Pacific Disaster Center, 2006).

Between 1951 and 1982, the lower (northern) part of the Tunjuelo basin (see Fig. 1) was the most important area for urban development in the city, being settled by the poorest population of Bogotá (Osorio, 2007). This growth has been characterised by informality and lack of planning. The start of the urbanization of the mountainous area of the Tunjuelo River basin occurred in the 60s and 70s. This change in the land use caused loss of vegetation and erosion, which enhanced flood hazard (Osorio, 2007).

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The most damaging floods in the Tunjuelo basin have caused significant economic losses and fatalities (DPAE, 2003a, b).

The urban development of the watersheds located in the hills to the east of Bogotá (see Fig. 1) has a quite different characteristic to that of the Tunjuelo basin. Urbanization has taken place through both informal settlements and exclusive residential developments (Tamayo, 2013). In addition, protected forests cover most of the upper watersheds.

In this analysis the watersheds located in mountainous terrain that drain into the main stream of the Tunjuelo basin, as well as the watersheds in the Eastern Hills were considered. This includes 66 watersheds in the Tunjuelo River basin and 40 in the Eastern Hills of Bogotá (see Fig. 1). The remaining part of the urban area of the city covers an area that is predominantly flat, and is not considered in this study.

3.2 Methodology

The prioritisation of flood risk was carried out using watersheds in the study area as units of analysis. The watershed divides were delineated up to the confluence with the Tunjuelo River, or up to the confluence with the storm water system, whichever is applicable. First a delineation of areas exposed to flooding from these watersheds using simplified approaches was carried out. Subsequently a vulnerability indicator was constructed based on a principal component analysis of variables identified in literature as contributing to vulnerability. A sensitivity analysis was undertaken to test the robustness of the vulnerability indicator. From the vulnerability indicator a category (high, medium and low vulnerability) was obtained that was then combined with a categorisation of flash flood susceptibility previously generated in the study area to obtain a prioritisation category. A detailed explanation of the analysis is given in the following subsections.

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3.2.1 Delineation of exposure areas

Exposure areas were obtained from an analysis of the susceptibility to flooding. Areas that potentially can be affected by clear water floods and debris flows were determined using simplified methods that provide a mask where the analysis of exposed elements was carried out. The probability of occurrence and magnitude are not considered in the analysis, since the scope of the simplified regional assessment is limited to assessing the susceptibility of the watersheds to flooding.

Areas prone to debris flows were previously identified by Rogelis and Werner (2013) through application of the Modified Single Flow Direction model. These were complemented with methods to delineate areas prone to clear water floods. The areas found through these two approaches were subsequently combined, since debris flow dominated areas can also be subjected to clear water floods (Lavigne and Suwa, 2004). This provides a conservative delineation of the areas considered to be exposed to flooding.

In order to delineate the areas prone to clear water floods, or floodplains, two geomorphic-based methods were tested using a digital elevation model with a pixel size of 5 m as an input, which was obtained from contours. Floodplains are areas near stream channels shaped by the accumulated effects of floods of varying magnitudes and their associated geomorphological processes. These areas are also referred to as valley bottoms and riparian areas or buffers (Nardi et al., 2006).

The first approach is the multi-resolution valley bottom flatness (MRVBF) algorithm (Gallant and Dowling, 2003). This identifies valley bottoms based on the assumption that; the valley bottoms are low and flat relative to their surroundings; the valley bottoms occur at a range of scales; and large valley bottoms are flatter than smaller ones. The MRVBF algorithm identifies valley bottoms using a slope classification constrained on convergent area. The classification algorithm is applied at multiple scales by progressive generalisation of the DEM, combined with progressive reduction of the slope class threshold. The results at different scales are then combined into

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a single index. The MRVBF index utilises the flatness and lowness characteristics of valley bottoms. Flatness is measured by the inverse of slope, and lowness is measured by ranking the elevation with respect to the surrounding area. The two measures, both scaled to the range from 0 to 1, are combined by multiplication and could be interpreted as membership functions of fuzzy sets. While the MRVBF is a continuous measure, it naturally divides into classes corresponding to the different resolutions and slope thresholds (Gallant and Dowling, 2003).

In the second method considered, threshold buffers are used to delineate floodplains as areas contiguous to the streams based on height above the stream level. Cells in the digital elevation model adjacent to the streams that meet height thresholds are included in the buffers (Cimmery, 2010). Thresholds for the height of 1, 2, 3, 4, 5, 7 and 10 m were tested.

A third approach for the delineating of the floodplains, the modified topographic index (MTI) proposed by Manfreda et al. (2011) was considered. This method is based on the strong correlation observed between the topographic index and areas exposed to flood inundation. Flood prone areas are considered to be those that have a topographic index above a given threshold (Di Leo et al., 2011). The threshold of the index that was used for the delineation corresponds to the value proposed by Di Leo et al. (2011) obtained from the calibration of the method in Italian rivers. However, this was found not to be able to identify flood prone areas in the mountainous watersheds and was not further considered.

In order to evaluate the results of the MRVBF index and the threshold buffers, flood maps for the study area were used. These are available for only 9 of the 106 watersheds, and were developed in previous studies through hydraulic modelling for return periods up to 100 years. The delineation of the flooded area for a return period of 100 years was used in the nine watersheds to identify the suitability of the floodplain delineation methods to be used in the whole study area.

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3.2.2 Choice of indicators and principal component analysis for vulnerability assessment

In this study vulnerability in the areas identified as being exposed is assessed through the use of indicators. The complexity of vulnerability requires a reduction of available data to a set of important indicators that facilitate an estimation of vulnerability (Birkmann, 2006). To this end, principal component analysis was applied to variables describing vulnerability in the study area in order to create composite indicators (Cutter et al., 2003). The variables were chosen by taking into account their usefulness according to literature, and were calculated using the exposure areas as a mask.

Figure 2 shows the variables chosen to explain vulnerability in the study area. These are grouped in socio-economic fragility, lack of resilience and physical exposure. The variables are classified according to their social level (individual, household, community and institutional), hazard dependence and influence on vulnerability (increase or decrease). The third column specifies the spatial aggregation level of the available data. The three spatial levels considered are block, watershed and locality, where the locality corresponds to the 20 administrative units of the city. The data used to construct the indicators was obtained from the census and reports published by the municipality. For each variable the values were normalised between the minimum and the maximum found in the study area. In the case of variables that contribute to decreasing vulnerability a transformation was applied so a high variable value represents high vulnerability for all variables.

In order to construct the composite indicators related to socio-economic fragility and physical exposure, principal component analysis (PCA) was applied on the corresponding variables shown in Fig. 2. PCA reduces the dimensionality of a data set consisting of a large number of interrelated variables, while retaining as much as possible of the variation present in the data set. This is achieved by transforming to a new set of variables, the principal components (PCs), which are uncorrelated (Jolliffe, 2002). The number of components to be retained from the PCA was chosen

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by considering four criteria: the Scree test acceleration factor, optimal coordinates (Cattell, 1966), the Kaiser's eigenvalue-greater-than-one rule (Kaiser, 1960) and parallel analysis (Horn, 1965). Since the number of components may vary among these criteria, the interpretability was also taken into account when selecting the components to be used in further analysis, with each PC being considered an intermediate indicator. Subsequently a varimax rotation (Kaiser, 1958) was applied to minimise the number of individual indicators that have a high loading on the same principal component, thus obtaining a simpler structure with a clear pattern of loadings (Commission, 2008). The intermediate indicators (PCs) were aggregated using a weight equal to the proportion of the explained variance in the data set (Commission, 2008) to provide an overall indicator for socio-economic fragility and for physical exposure.

In the case of resilience, PCA was applied only to the variables education, illiteracy, access to information, infrastructure/accessibility, hospital beds and human resources in health. The other variables were treated independently due to their particular meaning in the resilience analysis (robberies and participation), the type of variable (risk perception, early warning), and lack of interpretation in the PCA (rescue personnel). Thus, lack of resilience is composed of four indicators, namely cohesiveness of the community, risk perception, early warning and rescue personnel plus the intermediate indicators obtained from the principal component analysis.

Cohesiveness of the community was identified as a factor that influences the resilience since the degradation of social networks limits the social organisation for emergency response (Ruiz-Pérez and Gelabert Grimalt, 2012). To construct this intermediate resilience indicator, the variables robberies and participation were chosen. Since there are only two variables to measure this aspect of resilience, PCA was not applied, and the average of the variables was used instead. The robberies that occur in the locality of the watershed were used as a proxy for trust, confidence and the level at which a proper post disaster environment could be expected, since a high probability of crime can affect the evacuation procedures and the process to recover.

Participation is measured as the percentage of eligible voters that voted in the most recent communal elections.

Risk perception and early warning were considered relevant aspects that influence the resilience and coping capacity. These indicators are Boolean. For risk perception a value of 1 was assigned to watersheds where floods have occurred previously and 0 if they have not. Likewise, watersheds where flood early warning systems are operational were assigned a value of 1 for the variable early warning.

In the case of rescue personnel, this variable was initially used in the PCA. However, it was found to increase with lack of resilience, therefore it was treated independently.

To combine all the resilience indicators into a composite indicator, weights summing up to 1 were assigned to the two intermediate indicators obtained from the PCA (see Sect. 4.3 for an explanation of the resulting intermediate indicators); lack of rescue personnel and lack of cohesiveness and participation. In order to take into account the weights obtained from the PCA in the composite indicator, equal weights were assigned to the individual indicators and the total weight assigned to the ones obtained from the PCA was proportionally assigned to each indicator according to the percentage of variability explained of the corresponding principal component.

Risk perception and early warning decrease the lack of coping capacity (Molinari et al., 2013), and therefore an equal negative weight was assigned to these indicators summing up to −0.2. This value was chosen so that their combined influence is less than the individual weight of the other four indicators. The sensitivity of this subjective choice was tested. The effectiveness of flood early warning is closely related to the level of preparedness as well as the available time for implementation of appropriate actions (Molinari et al., 2013). Due to the flashy behaviour and configuration of the watersheds in the study area, flood early warning actions are targeted at reducing exposure and vulnerability and not at hazard reduction.

The indicators corresponding to socio-economic fragility, lack of resilience and physical exposure were combined, assigning equal weight to the three components, to obtain an overall vulnerability indicator. The watersheds were subsequently

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categorised as being low, medium or high vulnerability based on the value of the vulnerability indicator.

3.2.3 Sensitivity of the vulnerability indicator

The influence of the subjective choices applied in the construction of the indicators was analysed. These include the PCA component selection, PCA rotation, and the weighting scheme used to combine the components to create the final indicator. To select the number of components to be retained from the PCA, as explained in Sect. 3.2.2, four criteria were assessed (the Scree test acceleration factor, optimal coordinates, the Kaiser's eigenvalue-greater-than-one rule and parallel analysis). For the PCA rotation five methods in addition to the varimax rotation were considered: unrotated solution; quatimax rotation (Carroll, 1953; Neuhaus, 1954); promax rotation (Hendrickson and White, 1964); oblimin (Carroll, 1957); simplimax (Kiers, 1994); and cluster (Harris and Kaiser, 1964). The weights used to construct the lack of resilience indicator were varied, as well as the weights used to combine the socio-economic fragility, lack of resilience and physical exposure to construct the composite vulnerability indicator. All possible combinations were assessed and the results in terms of the resulting vulnerability category (high, medium and low) were compared in order to identify substantial differences as a result of the choices of subjective options.

3.2.4 Categories of recorded damage in the study area

A database of historical flood events compiled by the municipality was used to classify the watersheds in categories, depending on the recorded damages. The database contains data on the date, location, affected persons, evacuated people and number of affected houses. The information on the flood events in the database was complemented with the reports issued by the municipality on each flood event where a more detailed description of the flood is made and the type of damage is described. Enough data for the analysis of flood events in 14 watersheds was collected. On the basis of these data a categorisation of damage was created considering only the impacts of the events, without taking into account the frequency of occurrence since the available records cover only the period from 2000 to 2012. A score from 0 to 10 was assigned to each watershed according to the impacts of the floods as shown in Table 1. A score of 0 implies that no flood damage has been recorded in the watershed for a flood event, despite the occurrence of flooding, while a score of 10 corresponds to watersheds where human losses or serious injuries have occurred. Intermediate scores take into account the need of evacuation, the number of houses affected, the depth of inundation, and the occurrence of structural damage. The watersheds were subsequently divided into high, medium and low categories of flood impacts based on three equal intervals of the score range.

3.2.5 Prioritization of watersheds

Due to the regional character and scope of the method applied in this study, a qualitative proxy for risk was used to prioritize the watersheds in the study area. A high priority indicates watersheds where flood events will result in more severe consequences. However, the concept of probability of occurrence of these is not involved in the analysis, since the analysis of flood hazard is limited to susceptibility.

In order to combine the vulnerability and susceptibility to derive a level of risk, a classification matrix was used (Greiving, 2006). Figure 3 shows the initial matrix used for the analysis. The corners corresponding to high susceptibility and high vulnerability and low susceptibility and low vulnerability (cells a and i) were assigned a high and low priority respectively, since they correspond to the extreme conditions in the analysis. The cells from b to h in Fig. 3 were considered to potentially correspond to any category (low, medium or high priority). All possible combinations of the matrix were tested, assessing the proportion correct of a contingency table comparing the obtained priority and the classification of watersheds, where flood damage records are available, in categories of recorded damage according to Table 1. Under this procedure,

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the resulting matrix corresponds to the best fit of the priority and the classification according to damage scores from flood records.

4 Results

4.1 Exposure areas

Figure 4 shows the results of the methods applied to identify areas susceptible to flooding through clear-water floods or debris-flows. Figure 4a shows the debris flow propagation extent derived for the watersheds of the Tunjuelo basin and the Eastern Hills by Rogelis and Werner (2013). Since the method does not take into account the volume that can be deposited on the fan, this shows the maximum potential distance that the debris flow could reach according to the morphology of the area, which is in general flat to the west of the Eastern Hills watersheds. A different behaviour can be observed in the watersheds located in the Tunjuelo river basin where the marked topography and valley configuration restricts the propagation areas.

Figure 4b shows the results obtained from the MRVBF index. The comparison of the index with the available flood maps in the study area shows that values of the MRVBF higher than 3 can be considered areas corresponding to valley bottoms. In areas of marked topography the index identifies areas adjacent to the creeks in most cases and the larger scale valley bottoms. However, in flat areas the index unavoidably takes high values and cannot be used to identify flood prone areas.

Figure 4c shows the result obtained from the use of buffer thresholds. The buffers that were obtained by applying different criteria (height above the stream level of 1, 2, 3, 4, 5, 7 and 10 m) were compared with the available flood maps. Areas obtained for a depth criterion of 3 m were the closest to the flood delineation for a return period of 100 years, and this value was chosen as appropriate for the study area.

In order to obtain the delineation of the exposure areas, the results of the debris flow propagation; the MRVBF index and the buffers were combined. The results of all three

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methods in flat areas does not allow for a correct identification of flood prone areas, and a criteria based on the available information and previous studies was needed to estimate a reasonable area of exposure. The resulting exposure areas are shown in Fig. 5.

4.2 Socio-economic fragility indicators

The results of the principal component analysis applying a varimax rotation are shown in Table 2. To establish the number of components to be retained in the PCA analysis four methods were applied; the Scree test acceleration factor; optimal coordinates; the Kaiser's eigenvalue-greater-than-one rule; and the parallel analysis. These resulted in 1, 2, 2 and 3 components to be retained respectively. From these it was decided to retain 2 principal components as this allowed a clear interpretation to be made for each of the components. The variables included in the first principal component are related to lack of well-being, while in the second these are related to the demographic characteristics. The two principal components account for 79 % of the variance in the data with the first component explaining 80 % of the variance (PVE) and the second 20 %.

Using the factor loadings (correlation coefficients between the PCs and the variables) obtained from the analysis (see Table 2) and scaling them to unity, the coefficients of each indicator are shown in the following equations:

$$P_{\mathrm{LofW}} = 0.10\mathrm{Whh} + 0.10\mathrm{UE} + 0.10\mathrm{PNBI} + 0.09\mathrm{Ho} + 0.11\mathrm{P} + 0.10\mathrm{Pho} + 0.09\mathrm{M} + 0.10\mathrm{LE} + 0.08\mathrm{QLI} + 0.10\mathrm{HDI} + 0.04\mathrm{G} \quad (1)$$

$$P_{\mathrm{demog}} = 0.29\mathrm{Pe12} + 0.19\mathrm{IS} + 0.32\mathrm{Age} + 0.20\mathrm{D} \quad (2)$$

The impacts of the indicators imply that the higher the lack of well-being the higher the socio-economic fragility, and equally the higher the demography indicator the higher the socio-economic fragility. Using the percentage of variability explained by each

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component, the composite indicator for socio-economic fragility is found as:

$$P_{\text{soc-ec}} = 0.8P_{\text{LofW}} + 0.2P_{\text{demog}} \quad (3)$$

4.3 Lack of resilience indicators

The loadings of the indicators representing lack of resilience obtained from the PCA are shown in Table 3. The Scree test acceleration factor, optimal coordinates, the Kaiser's eigenvalue-greater-than-one rule and parallel analysis resulted in 1, 1, 1 and 2 components to be retained respectively. Again 2 principal components were used; the first correlated with variables related to the lack of education and the second with variables related to preparedness and response capacity. These account for 97 % of the variance in the data with the first component explaining 53 % of the variance (PVE) and the second 47 %.

Using the factor loadings obtained from the analysis and scaling them to unity, the coefficients of each indicator are shown in the following equations:

$$P_{\text{LEdu}} = 0.33\text{LEd} + 0.32\text{I} + 0.35\text{LI} \quad (4)$$

$$P_{\text{LPrRCap}} = 0.26\text{Lr} + 0.39\text{Lb} + 0.35\text{LHRs} \quad (5)$$

In an initial analysis, the variable lack of rescue personnel was included in the principal component analysis. Results showed a high negative correlation of this variable with lack of education, illiteracy and lack of Internet access. This may be due to more institutional effort being allocated to depressed areas that are more often affected by emergency events in order to strengthen the response capacity of the community. Also civil protection groups rely strongly on voluntary work that seems to be more likely in areas with lower education levels.

Since the consideration of lack of rescue personnel changes the interpretation of the principal component that groups the lack of education and access to information indicator, it was decided to exclude it from the PCA and to consider this variable as an independent indicator (Lack of Rescue Capacity).

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In the analysis of robberies and community participation as variables describing cohesiveness of the community, it was found that the increase in crime is correlated with the lack of participation, describing the distrust of the community both of neighbours and of institutions. The corresponding composite indicator was calculated as the average of robberies and lack of participation.

The equation of Lack of Resilience is shown in Eq. (6). Equal weight was assigned to the indicators reflecting Lack of Education, Lack of Preparedness and Response Capacity, Lack of Rescue Capacity and Cohesiveness of the Community; and a weight of −0.1 to Risk Perception and Existence of Flood Early Warning.

$$P_{\mathrm{LRes}} = 0.27P_{\mathrm{LEdu}} + 0.24P_{\mathrm{LPrRCap}} + 0.25P_{\mathrm{LCC}} - 0.1P_{\mathrm{RP}} - 0.1P_{\mathrm{FEW}} \quad (6)$$

Once the indicator of lack of resilience was obtained it was rescaled between 0 and 1.

4.4 Physical exposure indicators

The principal component analysis of the variables selected for physical exposure shows that these can be grouped into two principal components that explain 82 % of the variability. The results of the analysis are shown in Table 4.

Using the factor loadings obtained from the analysis and scaling them to unity, the coefficients of each composite indicator are shown in the following equations:

$$P_{\mathrm{Ei}} = 0.32\mathrm{Ncb} + 0.37\mathrm{Niu} + 0.32\mathrm{Ncu} \quad (7)$$

$$P_{\mathrm{Ep}} = 0.38\mathrm{Nru} + 0.33\mathrm{Pe} + 0.28\mathrm{Dp} \quad (8)$$

Using the percentage of variability explained by each indicator, the composite indicator of physical susceptibility is found to be:

$$P_{\mathrm{ps}} = 0.52P_{\mathrm{Ei}} + 0.48P_{\mathrm{Ep}} \quad (9)$$

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4.5 Vulnerability indicator

The resulting vulnerability indicator was obtained through the equal-weighted average of the indicators for socio-economic fragility, lack of resilience and coping capacity, and physical exposure. Categories of low, medium and high vulnerability for each watershed were subsequently derived based on equal bins of the indicator value. The spatial distribution is shown in Fig. 6, as well as the spatial distribution of the three constituent indicators.

Conditions of lack of well-being are shown to be concentrated in the south of the study area. The demographic conditions are more variable showing low values (or better conditions) in the watersheds in the south where the land use is rural and in the north where the degree of urbanization is low due the more formal urbanization processes (see Fig. 6a). The spatial distribution of the indicator of lack of resilience and coping capacity (Fig. 6b) shows that the highest values are concentrated in the south-west of the study area where the education levels are lower and the road and health infrastructure poorer. The same spatial trend is exhibited by the preparedness and response capacity. The south of the study area corresponds mainly to rural use, thus the physical exposure indicator shows low values (see Fig. 6a). The highest values are concentrated in the centre of the area where the density of population is high and the economic activities are located.

The spatial distribution of the overall indicator and the derived categories show that the high vulnerability watersheds are located in the centre of the study area and in the west. These reflect areas of high physical exposure and were the socio-economic and resilience and coping capacity indicators contribute to high vulnerability conditions.

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4.6 Prioritization of watersheds according to the qualitative risk indicator and comparison with damage records

The proportion correct of all possible matrices according to Sect. 3.2.5 (see Fig. 3) resulted in the optimum matrix shown in Fig. 7a, the corresponding contingency matrix is shown in Fig. 7b with a proportion correct (PC) of 0.85.

The prioritisation level obtained from the application of the combination matrix to the total vulnerability indicator and the susceptibility indicator for each watershed is shown in Fig. 8a. The results were assigned to the watersheds delineated up to the discharge into the Tunjuelo River or into the storm water system, in order to facilitate the visualisation. The damage categorisation of the study area using the database with historical records according to Table 1 is shown in Fig. 8b with equal range categories classified as high, medium and low. This shows that the most significant damages, corresponding to the highest scores for the impact of flood events, are concentrated in the central zone of the study area. The comparison between Fig. 8a and b shows that the indicators identify a similar spatial distribution of priority levels in the central zone of the study area that is consistent with the distribution of recorded damage. This is reflected in the proportion correct of 0.85.

4.7 Sensitivity analysis of the vulnerability indicator

Figure 9 shows the results of all possible combination of choices for the analysis (PCA component selection, PCA rotation, and the weighting scheme) in terms of the resulting vulnerability category as explained in Sect. 3.2.3. The most influential input factors correspond to the weights used both in the construction of the lack of resilience indicator and in the construction of the total vulnerability indicator. The thick vertical bars for each watershed show the interquartile range of the total vulnerability indicator, with the thin bars showing the range (min–max). While the range of the indicator for some watersheds is substantial, the sensitivity of the watersheds being classified differently in terms of low, medium or high vulnerability was evaluated through the

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number of watersheds for which the interquartile range intersects with the classification threshold. For seven watersheds classified as of medium vulnerability the interquartile range crosses the upper limits of classification of medium vulnerability, while for four watersheds classified as of high vulnerability the range crosses that same threshold. For the lower threshold, only two watersheds classified as being of low vulnerability are sensitive to crossing into the class of medium vulnerability.

5 Discussion

5.1 Exposure areas

Existing flood hazard maps developed using hydraulic models that were available for a limited set of the watersheds in the study area were used to assess the suitability of the proposed simplified methods to identify flood prone areas and extend the flood exposure information over the entire study area. The areas exposed to debris flows obtained through the MSF propagation algorithm show a good representation of the recorded events (Rogelis and Werner, 2013). However, in the eastern hills, where the streams flow towards a flat area, the results of the algorithms tend to overestimate the propagation areas since in these algorithms the flood extent is dominated purely by the morphology and the flood volume is not considered, which means there is no limitation to the flood extent.

Each of the methods applied for flood plain delineation has strengths and weaknesses, while the combination of the results from these methods provides a consistent and conservative estimate of the exposure areas. The MRVBF index allows the identification of valley bottoms at several scales. In the mountainous areas, zones contiguous to the streams are identified, and in areas of marked topography the results are satisfactory, allowing a determination of a threshold of the index to define flood prone areas. In the case of the buffers, a depth of 3 m seems adequate to represent the general behaviour of the streams. The combination of the methods allowed the estimation of exposure areas based on the morphology (low and flat areas), elevation difference with the stream level (less than 3 m) and capacity to propagate debris flows.

5.2 Representativeness and relative importance of indicators

The principal component analysis of the variables used to explain socio-economic fragility showed that the 16 variables that were chosen for the analysis could be grouped into two principal components strongly associated with the demographic characteristics of the population and the lack of well-being in the area. The latter was found to explain most of the variance in the data (80 % as shown in Table 2). The variables included in the demographic principal component, describe characteristics related to the origin of the population. Settlements of illegal origin are classified in the socio-economic strata 1 or 2 (for definition of variables see 2) and the urban processes involved in their development imply low standards of construction and deficit in public services. These characteristics of the settlements seem to be related with the percentage of dependent population (children, elderly and disabled) who in case of flooding are more susceptible to be affected (Cutter et al., 2003; Rygel et al., 2006).

The lack of well-being indicator is composed of 14 strongly correlated variables that are commonly used to measure livelihood conditions. Poverty does not necessarily mean vulnerability, though the lack of economic resources is associated with the quality of construction of the houses, health and education, which are factors that influence the capability to face an adverse event (Rygel et al., 2006). The variable "women-headed households" is correlated with the principal component related to lack of well-being as identified by Barrenechea et al. (2000). Even if this condition of the families is not necessarily a criteria related to poverty, women-headed households with children are related to vulnerability conditions. The woman in charge of the family is responsible for the economic, affective and psychological well-being of other persons, specially her children and elderly, in addition to domestic tasks and the family income. This condition suggest more assistance during emergency and recovery (Barrenechea et al., 2000).

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In the case of the lack of resilience indicators, the principal components related to education and response capacity can explain 99 % of the variance of the data. The percentage of variability explained by each principal component is approximately equal (53 and 47 %).

Regarding the physical exposure, the density of the built environment is a factor that highlights those areas where significant structural losses might be expected from a hazard event (Cutter et al., 2003). The variables community infrastructure, industrial units and commercial units are strongly correlated, representing the exposed activities and social infrastructure in the flood prone areas. These explain 51 % of the variability. On the other hand, the principal component composed of the number of residential units, population exposed and density of population represents the sector of the exposed elements related to the population and their property. This principal component explains 49 % of the variability. Physical vulnerability is commonly expressed in terms of a vulnerability curve that is based on the relation between hazard intensities and damage data. Different types of elements at risk will show different levels of damage given the same intensity of hazard (Jha et al., 2012; Albano et al., 2014; Liu et al., 2014). The degree of flood-induced damage to structures is determined by many factors, including water level, flow velocity, suspended and floating load, contaminants in the water, and flood duration. Therefore each vulnerability 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 (Luino et al., 2009; Jonkman et al., 2008). The method that was applied does not involve hazard intensity explicitly and different levels of physical susceptibility are not considered. The indicators used to express exposure and physical susceptibility imply that the more

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elements exposed the more damage, neglecting the variability in the degree of damage that the exposed elements may have.

5.3 Sensitivity of the vulnerability indicator

The results of all possible combinations of variations of the PCA component selection, rotation and weighting, show that of the 106 watersheds, the interquartile ranges cross the thresholds between categories of low, medium and high vulnerability in only 13 cases. This means that only these 13 watersheds are sensitive to the criteria selected for the analysis. In 11 of these, the category changes between medium vulnerability and high vulnerability and in the remaining two the change is from low to medium vulnerability. Watersheds with values of the vulnerability indicator out of the intermediate ranges of the thresholds are robust to the change in the modelling criteria.

The impact on the proportion correct of the priority classification of a shift of category of the 13 watersheds mentioned above can only be assessed for two watersheds, where flood records are available and a category according to Table 1 could be obtained. These correspond to watersheds number 39 and 1014 in Fig. 9, where the interquartile range crosses the threshold between high and medium vulnerability. In the case of watershed number 39, the susceptibility to flooding is classified as low, therefore, from Fig. 7a the priority is low regardless of the vulnerability level. Thus, the contingency matrix in Fig. 7b remains unchanged. In the case of watershed number 1014, the susceptibility level is high; therefore according to Fig. 7a the priority can vary from medium to high. This change has no impact in the proportion correct of the contingency matrix shown in Fig. 7b since the observed damage score of this watershed is low (the classification is incorrect regardless the change from medium to high).

The impacts on the contingency matrix shown in Fig. 7b cannot be assessed further due to the impossibility to obtain an observed damage score for the other 11 sensitive watersheds since there are no flood records for these.

Considering the sensitivity of the final priority, in 4 of the 13 sensitive watersheds, the susceptibility is low, then according to the classification matrix in Fig. 7a the priority does not change. In 2 watersheds the vulnerability can change from low to medium (see Fig. 9) and the corresponding susceptibility for these watersheds is medium, therefore from Fig. 7a the priority continues to be medium regardless of the possible change in vulnerability. In the seven remaining watersheds, vulnerability can vary between high and medium and the susceptibility is classified as high or medium, therefore from Fig. 7a the priority can vary between medium and high, with these being the only possible changes of priority in the analysis. This means, that of the 106 watersheds that were prioritised only 7 (7 %) are sensitive to change priority (high/medium), which reflects robustness in the analysis.

The difference between the threshold to separate low and medium vulnerability and the vulnerability indicator value of the first watershed classified as medium vulnerability is 0.08. This indicates that an increase in the threshold up to this value does not change the priority classification. A decrease of this threshold of 0.02 implies the inclusion of two watersheds in the medium vulnerability category. An increase or decrease of 0.01 in the threshold to separate medium and high vulnerability implies the decrease or increase of priority level respectively of one watershed. This implies that the watersheds can be grouped into categories with a low sensitivity to variation in the chosen threshold.

5.4 Interrelations between susceptibility and vulnerability in the prioritization indicator

The susceptibility indicator (see Fig. 8a) was obtained from the combination of a morphometric indicator and a land cover indicator. The former is associated to the natural condition of the watersheds and the latter linked to the anthropic influence. The watersheds located in the lower Tunjuelo river basin show high or medium susceptibility level driven by relatively good morphometric conditions but poor land cover indicators, contrary to the case of the Eastern Hills watersheds where the main contributor to susceptibility is the morphometry. In terms of vulnerability (see Fig. 6d), the watersheds in the lower Tunjuelo river basin show high values reducing towards the north of the study area in the Eastern hills. In the lower Tunjuelo river basin the high level of vulnerability and susceptibility is linked through the land cover that is an explicit indicator in the susceptibility analysis and that in the vulnerability analysis is an implicit factor in the physical exposure. This area of the city has been subjected to an informal urbanization process where the poorest self-build without regulation. The informal urbanization is acknowledged as one of the factors that contribute to degradation of the urban environment, leading to poor land cover conditions.

Land cover was identified as a key aspect in the flood susceptibility conditions of the area. Rogelis and Werner (2013) concluded that even if morphometric parameters of the watersheds show a high disposition for debris flow, land cover can compensate and reduce the susceptibility. On the contrary, if good morphometric conditions are present but deterioration of the watershed takes place the danger increases. Moreover, the influence of land cover is crucial for the hydrologic response of the watersheds and deterioration of land cover through urbanization or soil degradation leads to increases in discharges that modify the hazard conditions of the watershed. Therefore, the urban processes that take place in some areas produce a change in the environment that influences both vulnerability and susceptibility defining a complex cycle that builds up risk conditions.

Land cover reflects a very complex interrelation between the external and internal dimensions of vulnerability. Bohle (2001) describes the internal dimension of vulnerability as defencelessness and insecurity, or the lack of capacity to anticipate, cope with, resist and recover from the impacts of a hazard. In contrast, the external dimension involves exposure to risks and shocks. From the results of this priority analysis it is shown that the internal dimension of vulnerability can influence the external, through the modification of the environment. In the highest priority watersheds poor people settle, often illegally, in sensitive environmental areas and where they are more exposed (flood plains and steep slopes). The characteristics inherent to illegal

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urbanization (lack of urban services, lack of infrastructure, unplanned development, obstruction of streams, deforestation, increase of impervious surfaces, modification of floodplains) contribute to exacerbate hazard through the increase of flood frequency, magnitude and extent, increasing exposure and risk levels.

The resulting vulnerability-susceptibility combination matrix shown in Fig. 7a, shows that the recorded damage in the study area reflects conditions of low priority in cases were the susceptibility indicator is low regardless of the vulnerability. Conversely, when the susceptibility is high or medium, high vulnerability entails high priority and a reduction in the vulnerability level reduces the priority to medium levels. The proportion correct of the combination matrix with the classification of the watersheds obtained from recorded damage can be interpreted as high (0.85). This correspondence can be observed in the spatial distribution of the priorities compared with the categories of recorded damage shown in Fig. 8, where high priority watersheds are located in the lower (northern) basin of the Tunjuelo river. On the other hand, the priority classification shows watersheds in medium and high priority that do not have flood damage records, this highlights the complexity of the comparison since the non-occurrence of flood damage in the last ten years does not mean that it cannot occur in the future.

6 Conclusions

Vulnerability at regional level was assessed on the basis of a principal component analysis carried out with variables recognized in literature as relevant. Exposure areas obtained from simplified flood analysis were delineated at regional level to provide a mask where vulnerability variables were extracted. The vulnerability indicator obtained from the principal component analysis was combined with an existing susceptibility indicator providing a priority indicator useful for risk management at regional level.

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Fragility of the socio-economic system, lack of resilience to cope and recover and physical exposure as components of vulnerability can be expressed in terms of composite indicators. Each composite indicator is formed by constituent indicators that reflect the behaviour of highly correlated variables and that represent characteristics of the exposed elements. Fragility of the socio-economic system is expressed in terms of a demographic indicator and a lack of well-being indicator. Lack of resilience is formed by indicators related to the education of the population, preparedness and response capacity, rescue capacity, social cohesion and participation, the previous experience of the population and the existence of an operational flood early warning system. In the case of physical exposure, this is described in terms of an exposed infrastructure indicator and an exposed population indicator.

The combination of the indicators for fragility of the socio-economic system, lack of resilience and physical exposure allowed the calculation of a vulnerability indicator from which a classification into high, medium and low vulnerability was obtained for the watersheds of the study area. The sensitivity of the vulnerability indicator shows that the method is robust mainly for watersheds with indicator values out of the intermediate ranges where some category changes can occur in a limited amount of watersheds.

The final priority allocated to each watershed represents the best fit of the indicator system with the recorded damage in the study area with a proportion correct between the vulnerability-susceptibility combination matrix and the damage classification of 0.85. However, the prioritization shows watersheds in medium and high priority were no flood damage has been observed in the last 10 years, which is explained by the fact that the non-occurrence of flood events during this short period does not mean that flood damage will not take place in the future.

The methodology used in this paper allows a rapid assessment and prioritisation of regional flood risk based on available information in a developing mountainous city. The analysis provides insight into the drivers of vulnerability and risk in the area, with these being of crucial importance for planning risk management strategies. The results show that the prioritization is robust and efficient to cover large mountainous areas.

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The complex interaction between vulnerability and hazard is evidenced in the case study. Land cover, as a proxy of environmental degradation, shows the influence that vulnerability exerts on hazard and vice versa, establishing a cycle that builds up risk conditions.

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Table 1. Categories of recorded damage.

Score	Description
0	No recorded damage in the watershed.
1	Events that affect 1 house without causing injuries or human loss and without the need of evacuation.
2	Events that affect 1 house without causing injuries or human loss and with the need of evacuation.
3	Events that affect up to 5 houses without causing injuries or human loss, flood depth less than 0.5 m with evacuation of families.
4	Events that affect up to 5 houses without causing injuries or human loss, flood depth higher than 0.5 m with evacuation of families.
5	Events that affect up to 10 houses without causing injuries or human loss with evacuation of families.
6	Events that affect 10–20 houses without causing injuries or human loss with evacuation of families, flood depth less than 0.5 m.
7	Events that affect 10–20 houses without causing injuries or human loss with evacuation of families, flood depth higher than 0.5 m.
8	Events that affect 20–50 houses without causing injuries or human loss with evacuation of families and possibility of structural damage in the houses.
9	Events that affect more than 50 houses without causing injuries or human loss with evacuation of families and possibility of structural damage in the houses.
10	Events that cause human losses or injuries.

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Table 2. Results of the principal component analysis for socioeconomic fragility indicators. NOTE: PVE corresponds to the percentage of variability explained by the principal component.

Variable	Symbol	Loadings
Lack of Well-being (PVE = 0.8)		
Women-headed households	Whh	0.94
Unemployment	UE	0.97
Poor-Unsatisfied Basic Needs Index	PUBNI	0.98
% Homeless	Ho	0.92
% Poor	P	0.99
Persons per home	Pho	0.94
Mortality	M	0.91
Life Expectancy	LE	0.94
Quality life index	QLI	0.86
Human Development Index	HDI	0.97
Population Growth Rate	G	0.57
Demography (PVE = 0.2)		
% of Children and Elderly	Age	0.84
% Disabled	D	0.67
% Population estrata 1 and 2	PE12	0.81
% Settlements of Illegal Origin	IS	0.64

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Table 3. Results of the principal component analysis resilience indicators.

Variable	Symbol	Loadings
Lack of Education (PVE = 0.53)		
Level of Education	LEd	0.94
Illiteracy	I	0.96
Lack of Access to Internet	LI	0.93
Lack of Prep. and Resp. Capacity (PVE = 0.47)		
Lack of Roads	Lr	0.80
Lack of Beds in Emergency Rooms	Lb	0.97
Lack of Human Resources in Health	LHRh	0.92

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Table 4. Results of the principal component analysis physical susceptibility indicators.

Variable	Symbol	Loadings
Exposed infrastructure (PVE = 0.52)		
Number of civic buildings	Ncb	0.86
Number of industrial units	Niu	0.96
Number of comercial units	Ncu	0.85
Exposed population (PVE = 0.48)		
Number of residential units	Nru	0.91
Population exposed	Pe	0.85
Density of population	Dp	0.78

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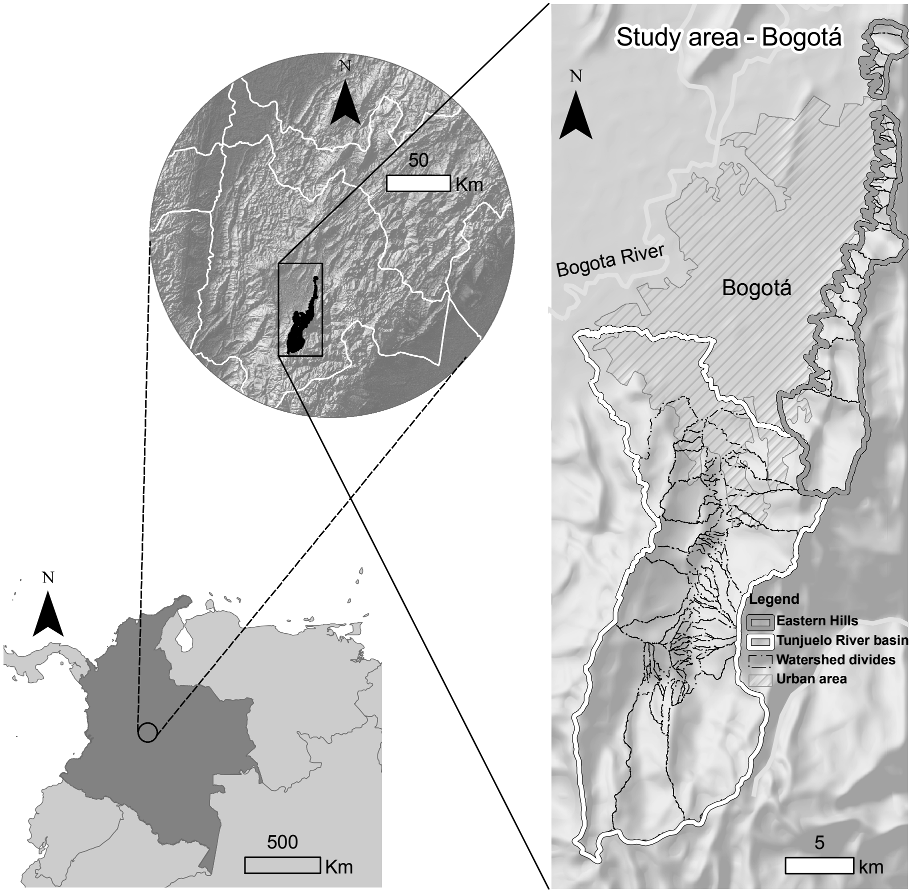

Figure 1. Location of the study areas.

Social levels	Variable	EoV	spatial level	Description
Socio economic Fragility				
Individuals	Age	Increases vulnerability	BLOCK	percentage <10 plus percentage >65
	Disability	Increases vulnerability	BLOCK	% of population having any sort of disability
	Unemployment	Increases vulnerability	LOCALITY	Unemployement rate
	Income	Increases vulnerability	LOCALITY	Unsatisfied basic needs index - UBN, % of homeless, % of poor population.
	Life expectancy	Reduces vulnerability	LOCALITY	Life expectancy.
Household	Household size	Increases vulnerability	LOCALITY	Average number of persons per household
	Woman-headed households	Increases vulnerability	LOCALITY	Percentage of families headed by women.
Community	Illegal settlements	Increases vulnerability	BLOCK	Percentage of illegal settlements.
	% of population of strata 1 and 2	Increases vulnerability	BLOCK	The socio-economic stratification system of Bogotá classifies the population into strata with similar economic characteristics on a scale from 1 to 6 with 1 as the lowest income area and 6 as the highest.
	Life conditions	Reduces vulnerability	LOCALITY	Life conditions index
	Human development index	Reduces vulnerability	LOCALITY	Human development index
	Demographic preassure	Increases vulnerability	LOCALITY	Population growth rate
	Child mortality	Increases vulnerability	LOCALITY	Chid mortality rate
Institutional	---	---	---	---
Lack of Resilience/Coping capacity/Recovery				
Individuals	Level of Education	Reduces vulnerability	LOCALITY	% of population with education level superior to high school
	Illiteracy	Increases vulnerability	LOCALITY	Illiteracy rate
	Access to information	Reduces vulnerability	LOCALITY	% of homes with internet access
Household	---	---	---	---
Community	Risk perception	Reduces vulnerability	Watershed	Occurrence of previous floods in the watershed yes/no
	Robberies	Increases vulnerability	LOCALITY	Crime robberies per 10000 inhabitants
	Participation	Reduces vulnerability	LOCALITY	% voters at last communal elections
Institutional	Infrastructure/ accessibility	Reduces vulnerability	LOCALITY	% of roads in good condition
	Early warning	Reduces vulnerability	watershed	Existence of flood early warning systems in the watershed YES/NO
	Hospital beds	Reduces vulnerability	LOCALITY	Hospital beds per 10000 inhabitants
	Health care HR	Reduces vulnerability	LOCALITY	Health care human resources per 10000 inhabitants
	Rescue personnel	Reduces vulnerability	LOCALITY	Rescue personnel per 10000 inhabitants.
Physical exposure				
Individuals	Population exposed to floods	Increases vulnerability	BLOCK	Number of people in flood prone areas
	Density	Increases vulnerability	BLOCK	people per km^2 in flood prone areas.
Household	Houses in flood prone areas	Increases vulnerability	BLOCK	Number of houses in flood prone area
Community	Comercial and industrial development in the flood prone area	Increases vulnerability	BLOCK	Number of commercial and industrial establishments in flood prone area.
	Community, cultural, health care and educational buildings in flood prone areas	Increases vulnerability	BLOCK	Number of community, social, cultural, health care infrastructure exposed
Institutional	---	---	---	---

Legend

Box format
- Hazard dependent
- Hazard independent

EoV- Effect on vulnerability
- Increases vulnerability
- Reduces vulnerability

Figure 2. Variables used to construct vulnerability indicators.

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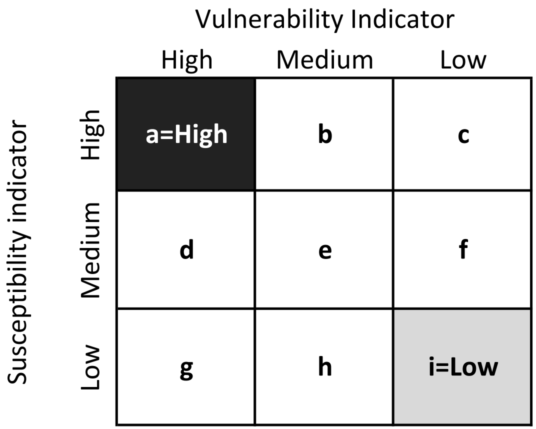

Figure 3. Initial matrix of priority.

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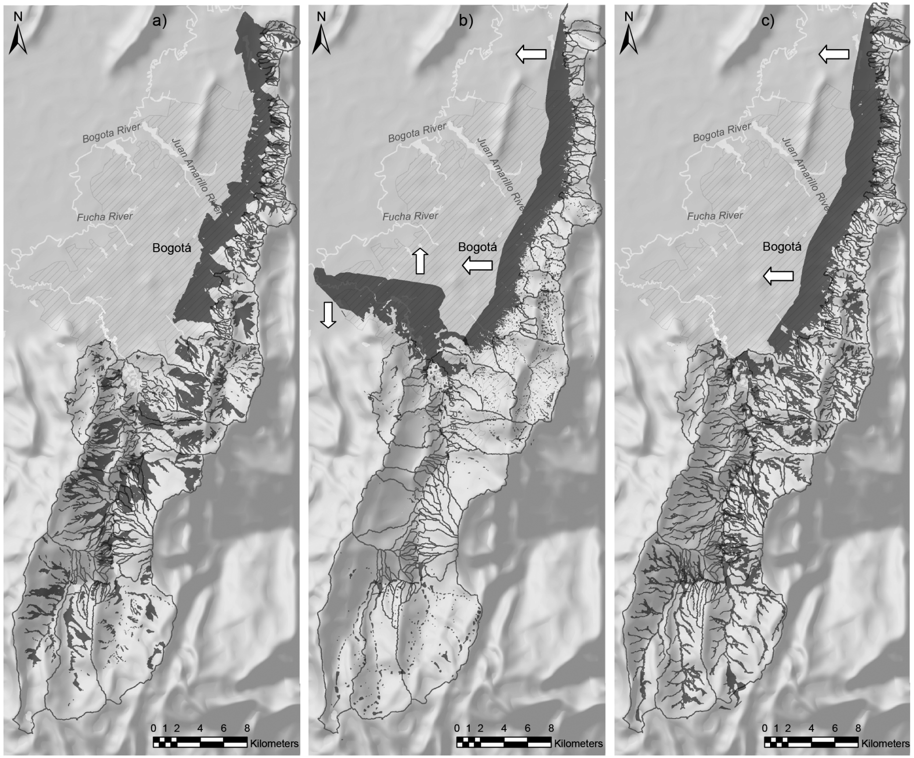

Figure 4. Clear water flood and debris flow susceptibility areas. Areas in dark grey in each map represent; **(a)** debris flow extent (Rogelis and Werner, 2013); **(b)** valley bottoms identified using the the MRVBF index; **(c)** buffers. In the case of maps **(b)** and **(c)**, the flood prone areas extend in the direction of the arrows over the flat area.

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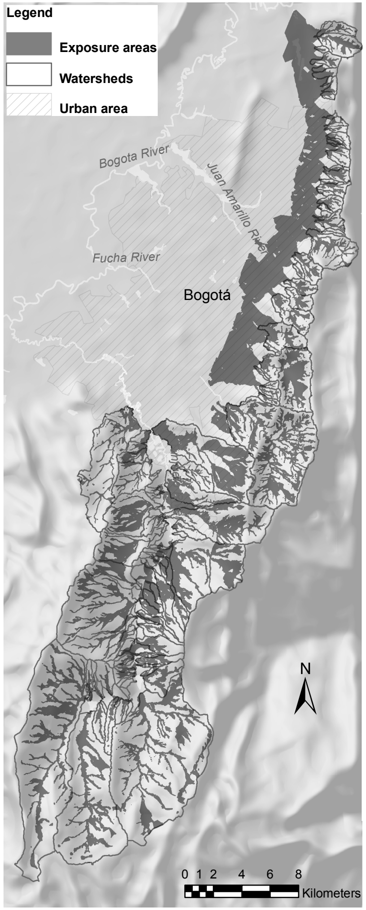

Figure 5. Exposure areas.

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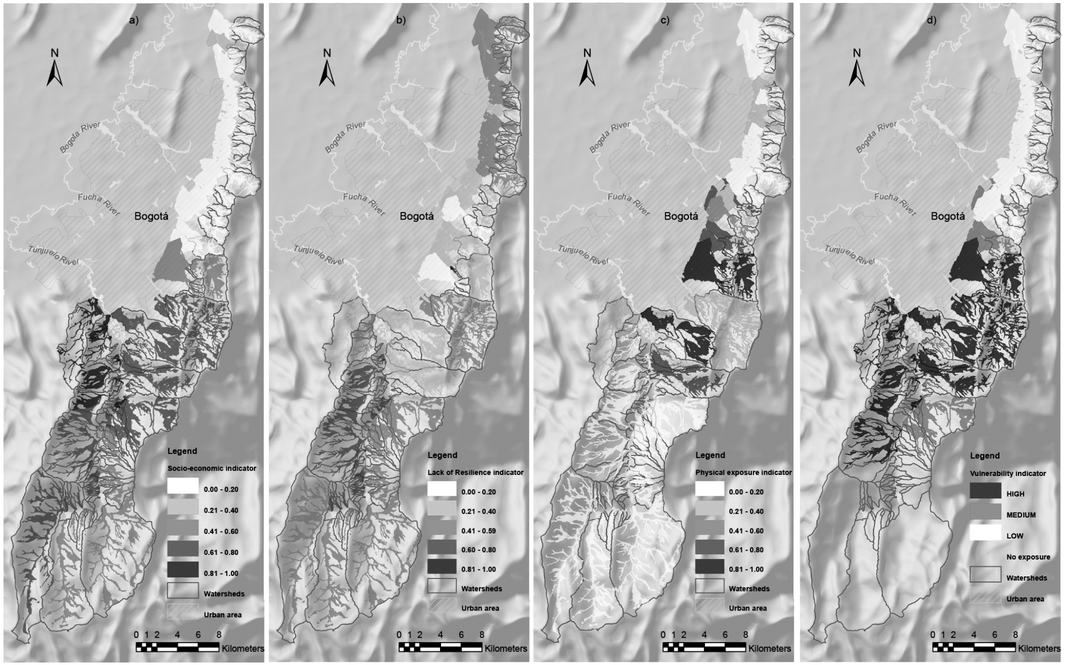

Figure 6. (a) Spatial distribution of the socio-economic indicator; **(b)** spatial distribution of the resilience indicator; **(c)** spatial distribution of the physical exposure indicator; **(d)** spatial distribution of the total vulnerability indicator.

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a) Vunerability-Susceptibility combination matrix

Susceptibility indicator \ Vulnerability Indicator	High	Medium	Low
High	**High**	**Medium**	**Medium**
Medium	**High**	**Medium**	**Medium**
Low	**Low**	**Low**	**Low**

b) Contingency matrix

i. 3x3 contingency matrix

Predicted priority \ Observed damage score	High	Medium	Low
High	7	0	0
Medium	0	3	2
Low	0	0	1

Proportion correct (PC)= 0.85

Figure 7. (a) Vulnerability–susceptibility combination matrix. **(b)** Contingency matrix.

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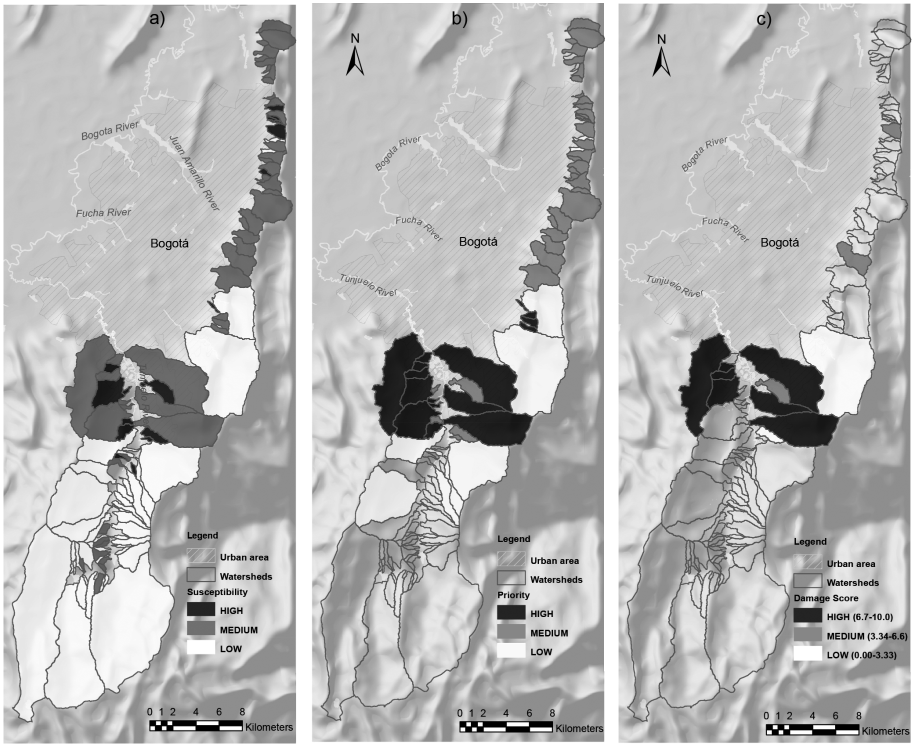

Figure 8. (a) Susceptibility classification of the study area. **(b)** Prioritisation according to the qualitative risk indicator. **(c)** Damage categorization.

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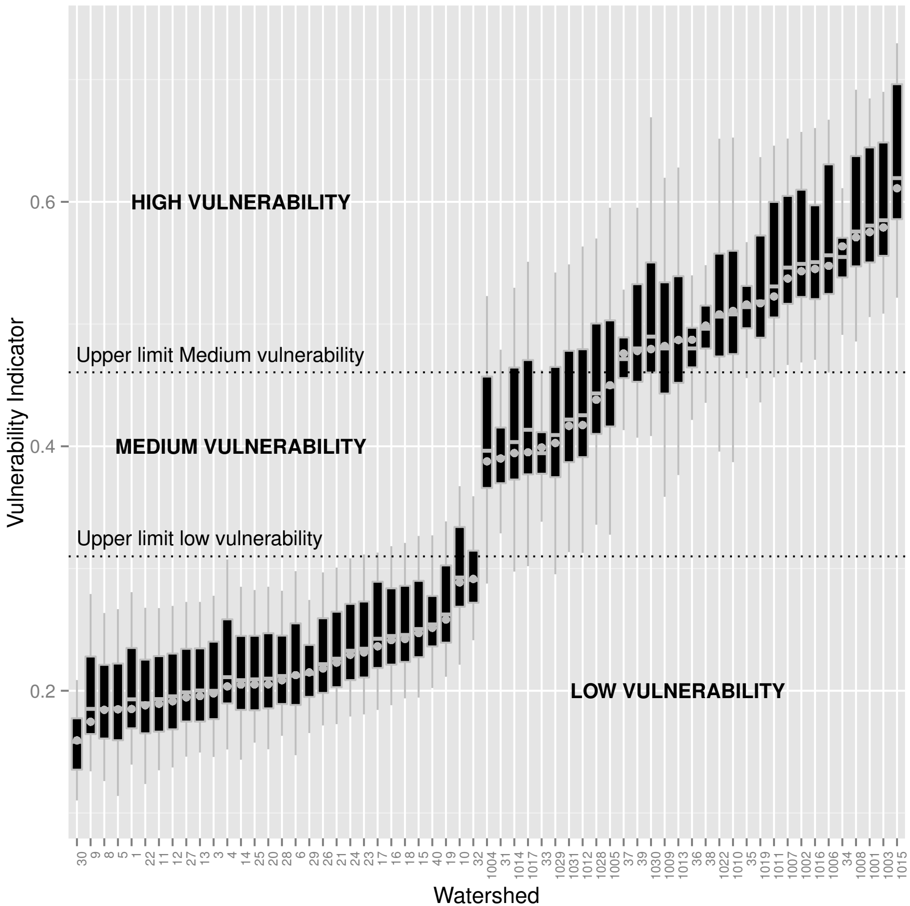

Figure 9. Sensitivity analysis of the vulnerability indicator. Note: the grey dots correspond to the value of the indicator obtained from the analysis explained in Sects. 4.1–4.5.

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