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ORIGINAL PAPER

A risk analysis for floods and lahars: case study in the Cordillera Central of Colombia

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Abstract The glacier-covered Nevado del Tolima in the Colombian Cordillera Central is an active volcano with potential lahars that might be more hazardous than those on Nevado del Ruiz. Furthermore, rainfall-triggered floods and landslides notoriously and severely affect the region. For effective disaster prevention, a risk analysis is of primary importance. We present here a risk analysis methodology that is based on the assessment of lahar and rainfall-related flood hazard scenarios and different aspects of vulnerability. The methodology is applied for populated centres in the Combeima valley and the regional capital Ibagué ($\sim$500,000 inhabitants). Lahar scenarios of 0.5, 1, 5, and 15 million m^3 volume are based on melting of 1, 2, 10, and 25 % of ice, firn and snow, respectively, due to volcanic activity and subsequent lahar formation. For flood modelling, design floods with a return period of 10 and 100 years were calculated. Vulnerability is assessed considering physical vulnerability, operationalized by market values of dwelling parcels and population density, whereas social vulnerability is expressed by the age structure of the population and poverty. Standardization of hazard and vulnerability allows for the integration into a risk equation, resulting in five-level risk maps, with additional quantitative estimate of damage. The probability of occurrence of lahars is low, but impacts would be disastrous, with about 20,000 people and more directly exposed to it. Floods are much more recurrent, but affected areas are generally smaller. High-risk zones in Ibagué are found in urban areas close to the main river with high social vulnerability. The methodology has proven to be a suitable tool to provide a first overview of spatial distribution of risk which is considered by local and regional authorities for disaster risk reduction. The harmonization of technical-engineering risk analysis and approaches from social sciences into common reference concepts should be further developed.

Keywords Risk analysis · Vulnerability · Natural hazard · Colombia · Combeima · Nevado del Tolima · Lahar · Cordillera Central

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1 Introduction

Ice-capped active volcanoes pose serious hazards to downstream population centres in many regions around the world, such as in the Andes, the Cascades in the United States, in Mexico or in Iceland. During the past events, loss ranging from widespread infrastructure damage to many thousands of deaths was recorded (Major and Newhall 1989). In Colombia, the 1985 Nevado del Ruiz and Armero disaster is most well known (Pierson et al. 1990; Thouret 1990). More recently, eruptions of the ice-covered Nevado del Huila volcano in 2007 and 2008 resulted in extremely large volcanic debris flows (lahars) with volumes in the range of tens to hundreds of millions cubic metres (Worni et al. 2012).

Nevado del Tolima, another ice-capped volcano in the Cordillera Central, lies in between the Nevados del Ruiz and Huila, approximately 30 km south of Nevado del Ruiz. The provincial capital city Ibagué is within the reach of its potential lahars (Cepeda and Murcia 1988; Thouret et al. 1995; Cantagrel et al. 1995; Huggel et al. 2007). Furthermore, rainfall-triggered floods and landslides notoriously affect the region. Hundreds of people were killed by different flood and landslide events in the past decades.

Government agencies such as the Colombian Geology and Mining Institute (INGEOMINAS) (e.g. Cepeda and Murcia 1988) or the Colombian Institute for Meteorology, Hydrology and Environmental Studies (IDEAM) made efforts to map volcano and flood hazards. Moreover, Thouret and Laforge (1994) presented a detailed hazard zone map of specific city quarters in Ibagué, but a comprehensive risk analysis including lahars and floods for the region has been missing so far.

Risk analysis and maps are valuable to support the risk evaluation and management process and to find appropriate risk reduction measures such as land-use planning, early-warning systems, preparedness and awareness-building activities (e.g. Bründl et al. 2009; Bell and Glade 2004).

In the past risk analyses for natural hazards focused more on technical and physical aspects of risk, but it is now widely accepted that risk results from interactions between natural hazards and vulnerable conditions (UNISDR 2011). While the term 'natural hazards' is generally considered a product of magnitude and probability of occurrence (e.g. Alcántara-Ayala 2002; Raetzo et al. 2002), vulnerability is a more contested concept. No clear scientific consensus has been reached so far as to how vulnerability is exactly defined and by which factors it is influenced (Cutter et al. 2003; Dikau and Weichselgartner 2005; Thomalla et al. 2006; Birkmann and von Teichman 2010), but recent research underlines that vulnerability is a product of specific spatial, socio-economic, cultural and institutional contexts (Kuhlicke et al. 2011). Accordingly, concepts have been developed that distinguish between different facets of vulnerability, including physical, social, economic, and cultural vulnerability (Tapsell et al. 2010).

There exist a large variety of approaches how to measure risk from a physical and technical point of view (e.g. Varnes 1984; Bründl et al. 2009). For a given scenario, it is theoretically possible to quantify physical loss (monetary value, deaths per year) applying the concept of Varnes (1984) who defines risk R as the product of vulnerability V, cost or amount of the elements at risk E, and the probability of occurrence of the event H (van Westen et al. 2006; Remondo et al. 2008; Zimmermann et al. 2005).

Physical vulnerability thereby is assessed by a variety of methods but generally refers to the susceptibility of elements at risk (e.g. people, buildings, roads) with respect to a hazard (Hufschmidt et al. 2005; Glade 2003). Often, it is expressed on a scale of 0 (no loss) to 1 (total loss) (Glade 2003) and depends in the case of buildings among others on the angle of the building to the flow direction, on construction material, age, the number of stories, the number of openings (e.g. Douglas 2007; Spence et al. 2004; Blong 2003), the type of hazard (e.g. earthquake, landslide, flood, etc.), and its magnitude (Glade 2003). The degree of loss is often expressed as monetary loss such as reconstruction costs or building value (Papathoma-Köhle et al. 2010). However, due to the difficulties and the required time to assess vulnerability as the degree of impact depending on the magnitude and the characteristics of the hazardous event and the characteristics of the elements at risk (Papathoma-Köhle et al. 2010), in many studies, vulnerability indicators represent the amount of elements at risk rather than actual measures of vulnerability (Castellanos Abella and van Westen 2007; Keiler et al. 2004; Moran et al. 2003; Liu et al. 2002).

Approaches to measure social vulnerability often develop and apply indicators and indices. Commonly used indicators for social vulnerability include, among others, education, age, class, gender, health, poverty, or ethnicity (e.g. Dikau and Weichselgartner 2005; Alcántara-Ayala 2002; Cutter and Finch 2008; Paton et al. 2010; Kuhlicke et al. 2011). However, there is no common set of social vulnerability indicators that is generally valid; in fact, the appropriate indicators may considerably vary among different local and social settings and the purpose of the study (Kuhlicke et al. 2011). Should the appropriate indicators be clear, essential problems still remain regarding the availability and accuracy of data (e.g. aggregation, generalization), especially in developing countries. Although recent years have seen much progress on the research of social aspects of vulnerability and risk, the measurement and assessment of social vulnerability continues to be a major challenge (Bara 2010; IPCC 2012).

Similarly, the integration of physical and social vulnerability components is complex and has to cope with different concepts in technical-engineering and social sciences fields. A few approaches have been presented and applied into practice in developed (e.g. Weichselgartner 2001) and developing countries (e.g. Castellanos Abella and van Westen 2007; Hegglin and Huggel 2008; D'Ercole and Metzger 2009). Although recent studies achieved such an integration by mapping technological risks using GIS (Armenakis and Nirupama in press), such studies are still rare. In fact, comprehensive vulnerability and risk assessments are often lacking, especially in the form of maps for the local areas and regions, as acknowledged in the recent IPCC Special Report on Managing Risks from Extreme Events (IPCC 2012).

Here, we build on existing concepts and combine different methods and modelling approaches to develop an index-based methodology that is able to assess and map risk across the scale of several population centres and urban districts of the Tolima—Combeima region in Colombia. The framework developed allows us to overcome some of the difficulties of integrating aspects of physical hazards and different facets of vulnerability.

We concentrate on hazards related to lahars and floods, and the corresponding analysis is based on flood and lahar modelling combined with geomorphological mapping based on field work and other studies. For the purpose of hazard and risk mapping, we develop a hazard index, considering hazard magnitude and return period, that allows us to integrate both lahar and flood hazards into one single scheme.

For the vulnerability analysis, we develop an index-based approach that considers several aspects of vulnerability as described in pertinent literature. The implementation of the concept into practice, however, is limited by data availability, a notorious problem for many studies (Tapsell et al. 2010). Given these limitations, we are able to consider market values of dwelling parcels and population density, as a measure of physical vulnerability, as well as people's age structure and poverty, which are among the most widely cited measures of social vulnerability. Both, hazard and vulnerability values, are standardized

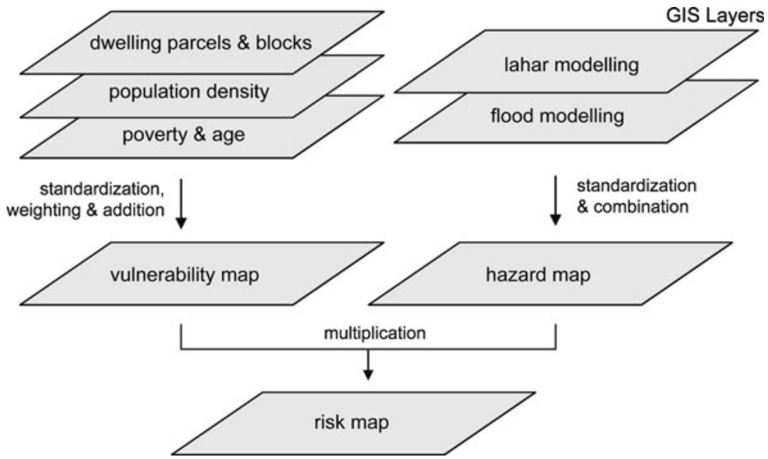

Fig. 1 Schematic risk analysis concept. Parallelograms represent GIS layers. The *left side* refers to the vulnerability and the *right* to the hazard. Vulnerability and hazard data are both standardized and combined generating a vulnerability and a hazard map. The values of both maps (ranging from 0 to 1) are subsequently multiplied to generate the risk map

into values from 0 to 1 and subsequently multiplied using a basic multi-criteria evaluation approach (Malczewski 1999), which results in the final risk analysis and mapping. Figure 1 shows the applied risk analysis concept schematically.

Our study thus presents an approach how theoretical concepts can be implemented into risk analysis and mapping, resulting in a number of consistent hazard, vulnerability and risk maps that have proved to be highly useful to local and regional authorities for decision-making and risk reduction efforts, such as land-use planning and implementation of early-warning systems.

2 Study area

The study area lies in the Colombian Cordillera Central (Northern Andes). The region hosts four glacier-clad volcanoes, namely Nevado del Ruiz, Nevado del Santa Isabel, Nevado del Tolima, and Nevado del Huila. Their summits range from ~4,960 to 5,360 m asl. Global public and scientific attention to the area has been strongly shaped by the Nevado del Ruiz/Armero catastrophe in 1985 (Pierson et al. 1990; Voight 1996). A moderate eruption of Nevado del Ruiz interacted with snow and ice in the summit area, and the resulting lahars destroyed the town of Armero, with approximately 23,000 people being killed (Pierson et al. 1990). This number makes Armero the worst known lahar disaster.

Nevado del Tolima volcano (5,220 m asl, 4°36′N, 75°20′W) lies approximately 30 km south of Nevado del Ruiz. The caldera of Nevado del Tolima opened the first time around 140000 years ago (Thouret et al. 1995). Thereafter, Thouret et al. (1995) distinguish six eruptive stages over the past 16000 years, the last of which occurred between 3600 and 1700 years BP. Stratigraphical findings indicate several lahars reaching as far as 70 km downstream. They were probably triggered by volcano-glacier interactions. Minor eruptions with tephra falls and debris flows occurred in 1826, 1828, 1918, and 1943 (Thouret et al. 1995), all of which reached a low Volcano Explosivity Index (VEI) of 2 (Siebert et al.

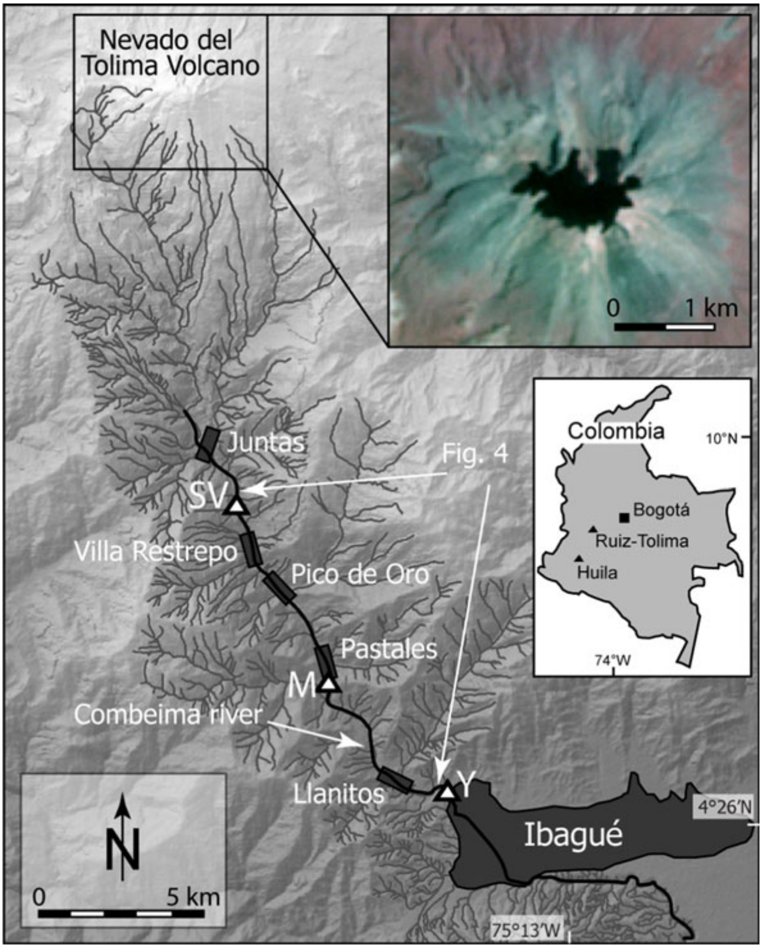

Fig. 2 Topographic situation of the Combeima valley with the Nevado del Tolima volcano at the headwaters and the city of Ibagué at the lower end. The most important population centres are indicated. *White triangles* refer to river gauging stations whose data were used in this study: *SV* San Vicente (destroyed during the June 2009 flood), *M* Montezuma, *Y* Yuldaima. The sites of the photographes in Fig. 4 are indicated by *arrows*. The *inset* in the *upper right* corner shows an ASTER satellite image of the Nevado del Tolima volcano, taken on 23 February 2007. The image is a composite of ASTER shortwave infrared channels 4, 5, 6 that allows for a clear delineation of the ice cap's extent (in *black*) (note the different scale of the *inset*)

2011). Since then, there has been fumarolic activity, especially southwest of the crater (Cepeda and Murcia 1988; Mora Paez et al. 1994; Núñez Tello 1996; Huggel et al. 2007). The current period of relatively low activity lasts approximately 1700 years and exceeds the average time interval of around 1000 years between the eruptive stages mentioned above. With respect to lahars, the eruptive history and its geomorphological instability render Nevado del Tolima more hazardous than Nevado del Ruiz (Thouret et al. 1995).

Our risk analysis is applied for the Combeima valley. The Combeima river drains ~45 % of the glaciers on Nevado Tolima towards its southern flank (Fig. 2).

Figure 3 presents a longitudinal profile and the main geomorphological units along the Combeima river between the ice-capped summit and Ibagué, the capital of the Department

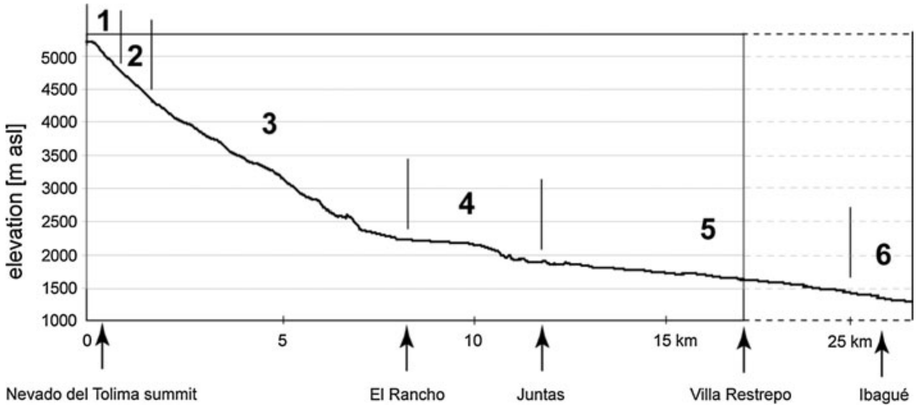

Fig. 3 Longitudinal profile along the Combeima river from the summit of Nevado del Tolima to Ibagué. Important geomorphological units include (see *numbers* indicated in figure): *1* present ice cover; *2* Holocene andesitic and basaltic lava flows with high resistance to erosion, and recent glacial moraines (~nineteenth century) with grain size of 50–60 % blocks, 15–25 % gravel, 5–10 % sand and 15–25 % fines; *3* pyroclastic flow and surge deposits, partly also andesitic lava; *4* pyroclastic flow and surge deposits overlaid by recent alluvium and debris flow/lahar deposits in the channel; *5* unconsolidated recent alluvial and debris flow or lahar deposits. Composition and grain size is varying but generally can be indicated as 35–50 % blocks, 20–30 % gravel, 10–20 % sand and 10–25 % fines. Blocks reach diameters up to 1.5–4 m; *6* Ibagué fan, composed by volcaniclastic, fluvial and debris flow deposits. From Thouret and Laforge (1994), Thouret et al. (1995); INGEOMINAS (2009) and own field studies

of Tolima, which is located ~30 km from the summit. The Combeima river flows through the city which counts approximately 500,000 inhabitants. The city has been built on a volcaniclastic fan with deposits from lahars and pyroclastic flows having their source on Nevado del Tolima (Thouret and Laforge 1994; Vergara Sanchez and Moreno Espitia 1992). The most populated centres in the Combeima valley apart from the city of Ibagué are the villages of Juntas, Villa Restrepo, Pico de Oro, Pastales, and Llanitos (~100–300 inhabitants each). Furthermore, scattered farms in the main valley and on higher slopes are widespread.

In addition to volcanic hazards, people, infrastructure, and the building stock in the Combeima valley and Ibagué are exposed to floods from the Combeima river. In the past, rainfall-triggered floods have repeatedly affected the region and claimed lives (Huggel et al. 2010). Particularly problematic is thereby that many people, especially the poor, live directly at the margin of the Combeima. The most recent major flood event occurred in June 2009 (Fig. 4). In addition to volcano and flood hazards, landslides from steep slopes and tributary valleys threaten the Combeima valley. This type of hazard is not a focus of this paper but has been studied by Huggel et al. (2010).

3 Data

3.1 Topography, cadastral and discharge data

A digital elevation model (DEM) derived from the Shuttle Radar Topography Mission (SRTM) in 2000 (Rabus et al. 2003) was obtained from IGAC (Geographic Institute Augustín Codazzi) in a 30-m resolution that was processed in collaboration with NASA at

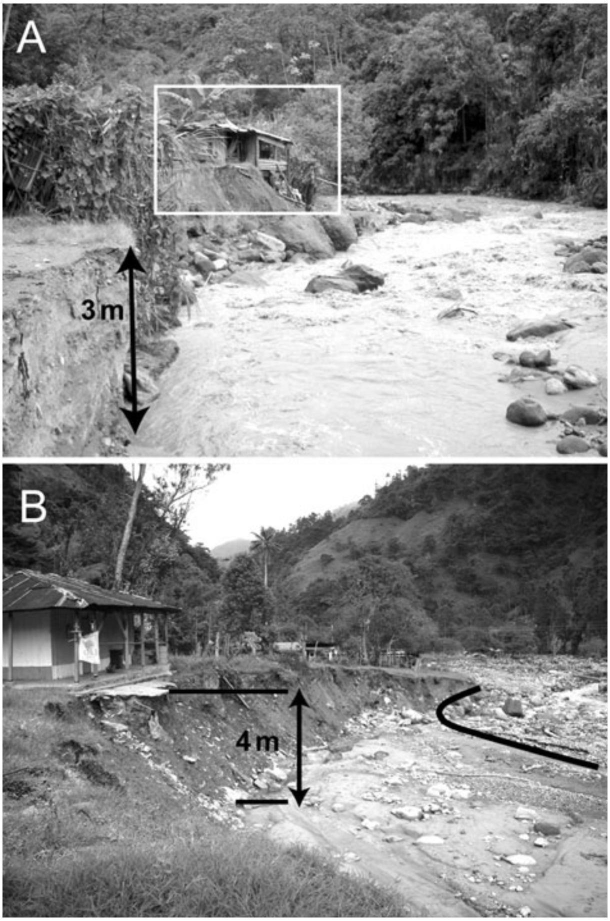

Fig. 4 Two sections of the Combeima after the 7 June 2009 flood. Site **A** is located between Llanitos and Ibagué and shows one of many poorly built residential structures (*rectangle*) directly at the margin of the river. Site **B** represents an upstream river section between Juntas and Villa Restrepo (Fig. 2). At both locations, the flood cut back the bank by several metres (*black line* indicates former river margin), resulting in widespread destabilization of the ground, roads, bridges, residential buildings, etc. (photographs taken in July 2009 by C. Huggel)

this improved resolution. An evaluation of the accuracy of the DEM was performed using 36 selected differential GPS elevation measurements along the Combeima river ranging from 1089 to 1832 m asl. The evaluation resulted in a vertical root mean square error (RMSE) of 8.7 m. A DEM of higher spatial resolution was not available. However, digital contour lines with an equidistance of 1 m were provided by CORTOLIMA (Tolima Regional Corporation) for the village of Villa Restrepo and served to enhance the accuracy of the DEM within this perimeter.

Digital cadastral data including the perimeters of houses and dwelling parcels of the five villages were provided by the Department of Land-Use Planning of Ibagué. The maps date from 2005 and the scale ranges from 1:5,000 (Pastales) to 1:1,750 (Pico de Oro). CORTOLIMA also provided a digital cadastral map of Ibagué. The cadastral data are shown in the hazard, vulnerability, and risk maps of this study.

Table 1 Measured maximal annual discharge at three gauging stations along the Combeima valley (Fig. 2)

Years	Q_{max} (m^3/s)		
	San Vicenze, 1750 m asl	Montezuma, 1450 m asl	Yuldaima, 1220 m asl
1980		73.0	
1981		40.6	
1982		38.7	
1983		33.1	
1984	25.4	30.8	68.0
1985	16.5	34.8	37.6
1986	18.2	26.1	43.4
1987	26.0	29.1	18.5
1988	35.0	16.0	
1989		22.0	116.2
1990	18.3	37.0	72.0
1991	12.0	24.7	38.0
1992	18.4	28.0	104.0
1993	34.2	29.8	85.1
1994	13.2	43.28	59.0
1995	21.3	57	192.6
1996	34.0	49	155.7
1997	14.4	16.5	142.6
1998	38.2	64.4	181.9
1999	12.4	38.8	43.7
2000	15.4		
2001		23.5	92.9
2002		17.1	154.3
2003		52.4	
2004		22.8	
2005		22.8	

Data provided by the Colombian Institute of Hydrology, Meteorology and Environmental Studies (IDEAM)

Discharge measurements at river gauges are maintained by IDEAM (Colombian Institute of Hydrology, Meteorology and Environmental Studies) for three sites along the Combeima river (Table 1). The measurement periods at the three stations are between 16 and 25 years (for location see Fig. 2).

3.2 Physical vulnerability data

Tax values of most dwelling parcels (in the villages) and housing blocks (Ibagué) were provided by the Municipality of Ibagué. Tax values typically are lower than market values, but we found no official relation between them except for an indication by an expert from the municipality that tax values may be around one-third of market values.

Several references were available for data on population for the five villages (Table 2). We evaluated the adequacy of the reference data during field surveys and considered either the most reliable reference or the mean value from several references. With respect to

Table 2 Population data for the five villages

Village	Years	References	Population	Mean	Considered for this study
Juntas	2007	Local inspector (estimate)	170		
	2006	CORTOLIMA (2006a)	229		
	2005	Sarmiento et al. (2005a)	221	207	207
V. Restrepo	2007	Barrios Peña and Olaya Marín (2007)	198		
	2006	CORTOLIMA (2006e)	254		
	2004	Pinto Randon (unpublished)	322	258	198
Pico de Oro	2007	Local inspector (estimate)	80		
	2006	CORTOLIMA (2006d)	290		
	2005	Sarmiento et al. (2005b)	86	152	83
Pastales	2006	CORTOLIMA (2006c)	171		
	2005	Alcaldía de Ibagué (unpublished)	361	266	266
Llanitos	2007	Local inspector (estimate)	256		
	2006	CORTOLIMA (2006b)	377	317	317

The references are ambiguous and do not always define the perimeter under investigation nor the method applied. In cooperation with local authorities, we determined the most reliable source (Villa Restrepo) or used the mean value of the sources considered reliable

physical resistance of buildings to hazard impact, our surveys indicated a relatively uniform building stock throughout the villages, and we therefore did not define an extra vulnerability parameter for this purpose.

For Ibagué, no population data were available on block, quarter or district level. Therefore, we estimated the population, based on SISBEN data (system for the identification and classification of potential beneficiaries for social programs) from May 2003 (Alcaldía de Ibagué 2003). SISBEN is an instrument of the National Department for Land-Use Planning and serves to evaluate socioeconomic characteristics (i.e. poverty) of the population. Categories range from 1 to 5, where 1 indicates the lowest socio-economic level. SISBEN data were available for all the 13 districts in Ibagué, four of which are located close to the Combeima river. Until 2003, 84.1 % of the population of the Department of Tolima has been registered in SISBEN (DNP 2003). Assuming that this percentage also applies for Ibagué, a calculation of the total population per district is possible (see Sect. 5).

3.3 Social vulnerability data

From different sources, age structure data of the five villages were available (Table 7). For Ibagué, age structure data were not available in accurate spatial resolution. However, the number of people per social class was available for every district in Ibagué (Table 8). SISBEN classifies the people into five social classes according to their socio-economic level, based on several indicators such as availability and quality of housing and basic public services, possession of durable goods, human capital endowments and current income. In the absence of other data, SISBEN is considered here as a useful indicator of social vulnerability.

Table 3 Characteristics of four lahar scenarios applied for hazard mapping

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Glacier area 2007 (m^2)	930,000	930,000	930,000	930,000
Drained by Combeima river (45 % of ice surface)	418,500	418,500	418,500	418,500
Mean ice thickness 1998 (m)	70	70	70	70
Ice volume drained by Combeima river (m^3)	29,295,000	29,295,000	29,295,000	29,295,000
Vertical melting of snow, firn, and ice (m)	1.2	2.0	8.8	20.6
Volume of melted snow, firn, and ice (m^3)	292,950	585,900	2,929,500	7,323,750
Melted percentage of total snow, firn, and, ice	1 %	2 %	10 %	25 %
Bulk density (g/cm^3)	0.6	0.7	0.8	0.85
Lahar water volume (40 %)	175,770	410,130	2,343,600	6,225,188
Lahar sediment volume (60 %)	263,655	615,195	3,515,400	9,337,781
Total lahar volume	439,425	1,025,325	5,859,000	15,562,969
Lahar volume used for modelling (mill. m^3)	0.5	1	5	15

4 Hazard analysis

4.1 Lahar volume and return period

The most important volcanic hazards in the Combeima valley are lahars triggered by pyroclastic flows and/or ice and rock avalanches (Huggel et al. 2007; Thouret et al. 1995). Cepeda and Murcia (1988) roughly mapped lahar hazard in the Combeima valley, assuming a probable total lahar volume of around 17 million m^3 and a possible total lahar volume of around 25 million m^3 corresponding to 10 and 15 % of the ice volume at that time drained by the Combeima river. Thouret et al. (1995) estimated potential lahar volumes from 4 million m^3 (moderate eruption, VEI 2–3) to 18 million m^3 (catastrophic eruption, VEI $\geq$ 5), assuming sediment entrainment ratios similar to that of the 1985 Rio Chinchina lahar at Nevado del Ruiz (1.5–4, by volume). In Thouret and Laforge (1994), four hazard zones around Ibagué's Yuladaima quarter are presented, corresponding to ice cap melting of 1–3, 5–10, 10–15, and > 15 %, respectively. Lahar volumes, though, are not indicated.

According to ground penetrating radar measurements in 1998, maximum ice thickness of the glaciers at Nevado del Tolima was 175 m with a mean of 70 m, whereas the ice extent was 1.04 km^2 in 2002 (Huggel et al. 2007) and 0.93 km^2 in 2007 (Table 3). This results in an ice volume of ~73 million m^3 for 2002 (Huggel et al. 2007) and ~65 million m^3 for 2007 based on the measured ice thickness in 1998. The lahar volume scenarios are based on a portion of 45 % glacier area draining towards the Combeima valley (whereas 55 % drain to other catchments) and bulk densities of snow, firn and ice between 0.6 and 0.85 g/cm^3 (Table 3), increasing with the vertical depth of the melting process, as proportionally more ice becomes melted and entrained. Based on similar lahar studies in Mexico (Schneider et al. 2008), at Merapi Volcano, Indonesia (Lavigne and Thouret 2003) and Mt. St Helens, USA (Pierson and Scott 1985), we assumed a lahar composition consisting of 40 vol% water and 60 vol% debris, corresponding to a sediment entrainment ratio of 2.5, which is around the average used in the studies mentioned above. In reality, water content can considerably vary along the flow path of one single event (Lavigne and Thouret 2003), and entrainment ratios are hard to quantify without intensive geomorphologic investigation and even then, uncertainties remain. In fact, for future events, it is virtually impossible to adequately determine the exact sediment entrainment ratios, and therefore, we consider the use of an average value a reasonable approximation.

Based on the above considerations, we defined four lahar volume scenarios of a total of 0.5, 1, 5, and 15 million m^3, approximately corresponding to 1, 2, 10, and 25 % melting and entrainment of snow, firn and ice (Table 3). The two larger scenarios are in the range of the studies mentioned above and are likely to include ice entrainment processes due to avalanche and failure processes in addition to melting and mechanical scouring. The smaller ones should cover lahars induced by minor eruptions, avalanches or heavy rain and are in the range of the smallest scenario of Thouret and Laforge (1994). Larger lahar scenarios are theoretically possible but are not considered in this study because of their low probability of occurrence.

To estimate the return periods for the four lahar volume scenarios, it should be considered that since the late Pleistocene (16000 years BP), the average interval between known eruptive events at Nevado del Tolima is around 1000 years. The interval between major eruptive events is 2000–4000 years (Thouret et al. 1995). For the 15 million m^3 scenario, we therefore define a return period of 1000 years. However, smaller lahars might have a shorter return period, because small-magnitude events generally occur more often than high-magnitude events (e.g. Hufschmidt et al. 2005; Iverson et al. 1998), as also documented on Nevado del Tolima in historical times (Thouret et al. 1995). Moreover, lahars can occur without eruption and be triggered by rainfalls, lake-dam breakout processes or earthquakes for instance (e.g. Thouret et al. 2000). Based on the existing lahar record, we define a return period of 100 years for the 0.5 million m^3 scenario, whereas that of the 1 and 5 million m^3 volume lahars lies between 100 and 1000 years. Although somewhat simplified, our return periods provide the adequate information required for hazard and risk analysis. Furthermore, due to the many uncertainties involved with volcanic eruptions and lahar formation, it is questionable whether more exact return periods could realistically be defined.

4.2 Flood discharge and return period

Based on maximum annual discharges for the Combeima river (Table 1), discharges for return periods of 10 years (Q10) and 100 years (Q100) were assessed applying Weibull and Gumbel statistical distributions (Table 4). While Q10 only slightly depends on the

Table 4 Estimated Q100 and Q10 for three gauging stations along the Combeima valley (Fig. 2) based on four different methods (for corresponding data, see Table 1)

Calculation method	San Vicente (m^3/s)		Montezuma (m^3/s)		Yuldaima (m^3/s)	
	Q10	Q100	Q10	Q100	Q10	Q100
Weibull exponential	36	40	57	64	198	244
Weibull polynomial	37	42	60	67	182	209
Weibull logarithmic	37	62	60	100	186	340
Gumbel	34	51	52	77	169	272

Unlike Q10, Q100 depends more strongly on the applied calculation method and should be regarded as indication value, though well suited for scenario building. For hazard modelling, we used the highest values to cover a worst-case scenario (Weibull logarithmic) applied method, Q100 more strongly differs according to the statistical distribution applied (Table 4). Although a longer discharge record (e.g. > 30 years) would increase the confidence of the results, the existing data series can be regarded as comparatively good and suited for scenario building. For flood modelling, we used the results of the logarithmic Weibull method, representing a worst-case.

4.3 Flood and lahar modelling

Lahar- and flood-prone hazard zones were assessed using two modelling programs. For lahars, we applied LAHARZ that was developed to delineate lahar hazard zones in a quick, objective, and reproducible way (Iverson et al. 1998). It is based on two semi-empirical equations derived from the analysis of generic lahar paths of 27 lahar events at nine volcanoes. The equations determine the inundated cross-sectional area and the inundated planimetric area as a function of lahar volume V (m^3). Input data are a DEM and defined lahar volumes (Table 3) as well as the height/length (H/L) ratio that determines the start of the deposition. As such, the H/L ratio also influences the runout distance of the modelled lahar. Based on the topography and field observations, we set the H/L ration at 0.35. LAHARZ has been extensively used in many lahar hazard studies, and several studies evaluated the effect of different DEMs on LAHARZ results, indicating that DEMs with a similar quality and resolution as used in this study are suitable for a first-order analysis of lahar inundation areas (Hubbard et al. 2007; Huggel et al. 2008; Muñoz-Salinas et al. 2009).

For flood modelling, we used HEC-RAS provided by the US Army Corps of Engineers (Brunner 2002). The program provides one-dimensional water surface profile calculations for steady flow (depth and velocity are constant) and unsteady flow (depth and velocity vary with time) in open channels (Dyhouse et al. 2003). We applied the freely available ArcGIS extension HEC-GeoRAS to extract the necessary topographic input information from the DEM. Manning's value is used to determine the friction loss in the model. Based on Chow (1959) and Barnes (1967), and additional field observation in the river channel, we set Mannig's value for the Combeima river at 0.045. Due to relatively uniform river bed conditions along the Combeima river, the range of variation of Manning's value is considered small. For the discharge data used, refer to Tables 1 and 4. We applied the same DEM as for LAHARZ and as described in Sect. 3.

4.4 Standardization and hazard delineation

For risk calculation, a standardization of hazard is necessary, typically expressing hazard between 0 (no hazard) and 1 (maximum hazard). In the following, we call the standardized hazard *hazard index*. There are limited references related to the development of hazard indices. Tingsanchali and Karim (2005), for instance, created hazard indices for flood hazards based on the flood depth and the flood duration. Azar and Rain (2007) transformed inundation maps for different discharges into hazard indices from 1 to 4. Hence, both indices are based on hazard magnitude alone and do not consider return periods. In contrast, the hazard concept approved by the Swiss Government (Raetzo et al. 2002) and also taken as a reference for the Andes region (Proyecto Multinacional Andino: Geociencias para las Comunidades Andinas 2007) expresses hazard by magnitude and return period. Inundation and deposition depth is taken as an indicator of hazard magnitude for floods and debris flows.

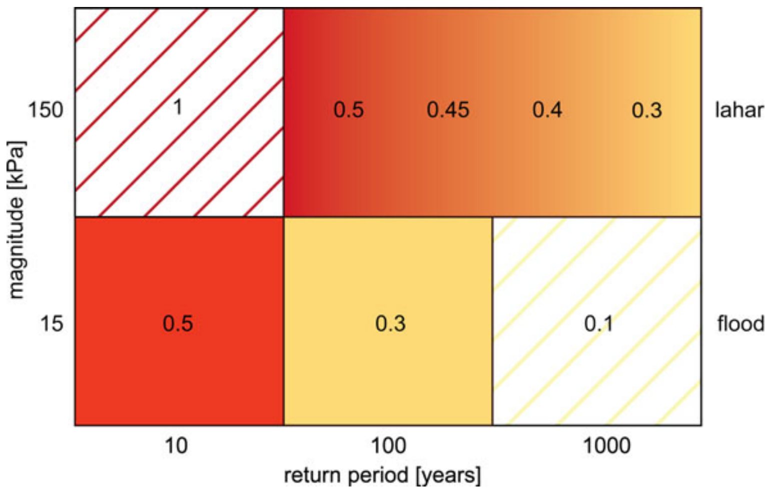

Fig. 5 Hazard index scheme with hazard indices based on magnitude and return period for mapping purposes. It should be noted that lahars with return periods of 10 years and floods with return periods of 1,000 years (*cross hatched*) are not considered because such scenarios are not supported by data and field observation. Indices are added when the area is prone to both lahars and floods

For the integration of hazards from lahars and floods into a common index scheme, differences with respect to the physical impact on built structures by either of the two processes have to be considered. Rather than inundation depth, we use here perpendicular pressure (kPa) against an obstacle to express hazard magnitude and to better compare the impacts of floods and lahars. We assessed the pressure (p) by multiplying the flow density (ρ) with the squared flow velocity (v^2). Flow velocities of lahars of 5 to 15 m/s are reported for the Combeima river (Cepeda and Murcia 1998) and at comparable sites at Nevado del Huila (Worni et al. 2012) and Nevado del Ruiz, Colombia (Verstappen 1992; Pierson 1995). Based on that, we set flow velocity at 10 m/s for lahars, and 4 m/s for floods, based on estimates from recent flood events. For the flow density, we assumed an average value of 1500 kg/m^3 for lahars (Neall 1976) and 1000 kg/m^3 for floods, resulting in pressures of 15 and 150 kPa for floods and lahars, respectively.

The effective velocity, density, and pressure values can vary considerably between different events and at different locations of one single event. However, for the development of the hazard index scheme (Fig. 5), we are primarily interested in a general estimate. The important point here is that floods and lahars differ by about one order of magnitude in terms of pressure. Consequently, the two pressure values (15 and 150 kPa) represent two magnitude levels in our hazard index scheme (Fig. 5).

Definition of return periods of 10, 100, and 1000 years was based on design periods (floods) and additionally on eruptive volcanic cycles of Nevado del Tolima volcano as described before. According to the hazard index scheme (Fig. 5), maximum hazard is found in the top left corner (high-magnitude, low return period) while low hazard is located at the lower right. It should be noted that lahars with return periods of 10 years and floods with return periods of 1000 years are not considered because such scenarios are not supported by data and field observation.

For the definition of the values between the lowest and highest hazard (i.e. 0.1 and 1, respectively), we took the reference of the definition of hazards zones, as given by Raetzo et al. (2002) and Proyecto Multinacional Andino: Geociencias para las Comunidades Andinas (2007), where magnitude and return period are the determinants of the hazard level. Both, magnitude and return period, differ by one order of magnitude in the scale of the scheme (15 and 150 kPa, and 10, 100 and 100 year return periods). A value of 0.5, for instance, is defined for a lahar with a 100-year return period and a flood with a 10-year return period because the magnitude of the lahar is one order of magnitude larger than that of a flood.

For hazard mapping, hazard indices are added if floods as well as lahars affect the area. For instance, the hazard index for an area affected by a flood having a return period of 100 years (hazard index = 0.3) and a lahar having a return period of 100 years (hazard index = 0.5) is 0.8. The maximum hazard index is always 1. Based on Fig. 5, the hazard maps (Fig. 6) were standardized to combine them with the vulnerability maps (Sect. 5) in order to calculate the risk (Sect. 6).

5 Vulnerability analysis

While in the past, many analyses were qualitative, recent years have seen an increasing emergence of quantitative metrics in the form of vulnerability indices and functions. Thereby, the spatial measuring dimension is sub-national (e.g. Petrova 2006; Cox et al. 2007; Aceves-Quesada et al. 2007), national to continental (e.g. Brooks et al. 2005; Cardona 2006; Greiving et al. 2006) or global (e.g. Peduzzi and Herold 2005). These methods are facilitated by a relatively good availability of social indicators at the national or sub-national level. Larger-scale studies using social vulnerability metrics have sporadically been achieved as well (Cutter et al. 2003; Fekete 2009; Armenakis and Nirupama in press). Especially in developing countries, studies at larger scales (community or household level) are often confronted with limited and inconsistent physical and social data (e.g. Hegglin and Huggel 2008). There exist a number of approaches to reduce the limitation in data availability, including participatory GIS studies that take advantage of involvement of stakeholders to generate spatially relevant, additional data (Tran et al. 2009). In this study, stakeholders were involved to support data generation for physical vulnerability (see following section).

The indicators of a vulnerability analysis may vary considerably. Because an important purpose of this study is to support risk reduction and management efforts, we defined indicators that assess endangered population and buildings, including location and density of population, density and economic value of buildings, as well as social vulnerability.

5.1 Physical vulnerability

Commonly, the built environment (e.g. buildings, roads, railways, electrical grids, water supply systems, etc.) and the population density are considered to be two important factors of physical vulnerability. As seen before, tax values of dwelling parcels in the five villages, and of housing blocks in Ibagué, were available. Because tax value data in the villages were incomplete, we conducted a house-by-house market value estimation of 389 dwelling parcels in March 2007. This work was done in collaboration with two local town inspectors. We then calculated the correlation between the market values and the tax values (Fig. 7) and estimated the market values for Ibagué where no house-by-house survey could be conducted. The correlation is based on 221 parcels in the five villages where both tax and market values could be evaluated, and we assume the correlation holds true for Ibagué

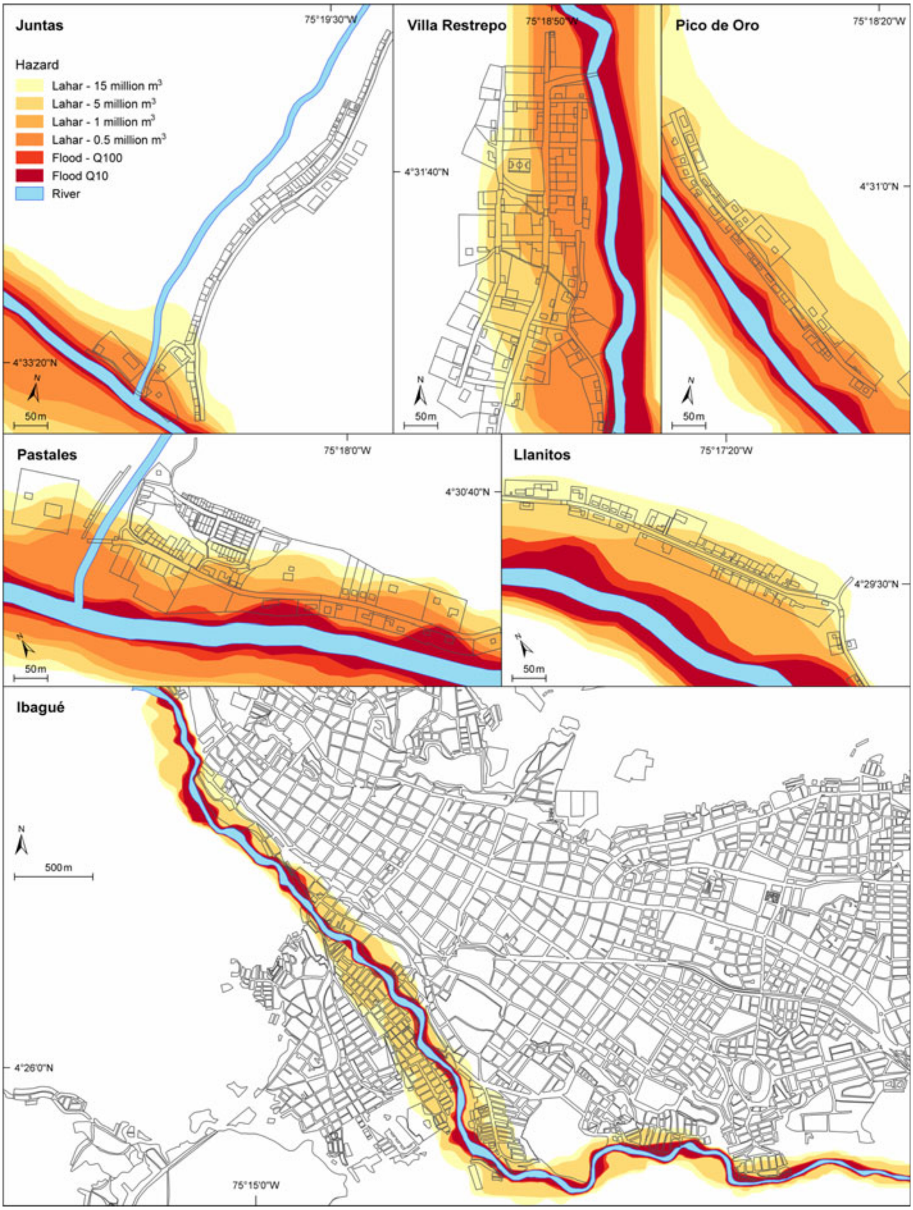

Fig. 6 Hazard maps based on four lahar and two precipitation-induced flood scenarios. The 0.5 million m^3 lahar stops before Llanitos and the 1 million m^3 lahar before Ibagué. Floods from tributaries and their impacts are not considered

as well. Market values were thereafter expressed per m^2 to make them comparable (Table 5). By far, the highest values per m^2 are found in Ibagué, where the housing density is high. The same is true for Juntas, where parcels are densely overbuilt.

Based on census and survey data (Sect. 3), we estimated the population of every specific parcel or block, assuming the population per unit (village, city district) being directly

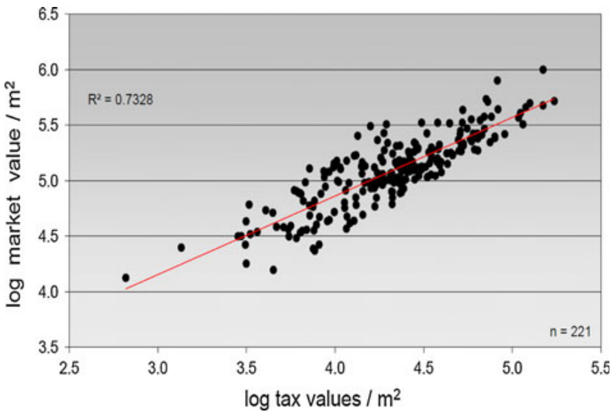

Fig. 7 Correlation and regression between 221 market values and tax values in the five villages

Table 5 Market values of dwelling parcels (villages)/blocks (Ibagué)

Location	Market value per parcel or block (million COP)		Market value/m^2 (COP)		Number of parcels/blocks under investigation
	Mean	Median	Mean	Median	
Juntas	37.6	25	311,492	211,268	74
Villa Restrepo	61.1	40	147,745	95,618	105
Pico de Oro	30.2	25	77,647	61,605	30
Pastales	32.5	12	105,371	100,671	105
Llanitos	30.1	20	98,165	66,620	75
Ibagué	3,061	1,162	766,040	450,488	389

2000 Colombian Peso (COP) corresponds to around 1 US Dollar

proportional to built-over area (area covered by buildings) per unit. Parcels that were known to be unoccupied were excluded. This assumption is a necessary simplification due to data limitations but should provide a reasonable average estimate. According to that, population density is highest in the Ibagué districts 11 and 12 and in Llanitos. The mean number of persons per dwelling parcel in the villages ranges from 2.6 to 4.2 (Table 6).

5.2 Social vulnerability

In case of a flood or lahar (or other natural hazards), children and elderly people are generally considered to be more vulnerable than other age groups (Hegglin and Huggel 2008; Liu et al. 2002; Cutter et al. 2000; Fekete 2009). We therefore estimated the percentage of children and elderly people, defining an upper age limit of 15 years for children and a lower age limit of 49 years for elderly people (Table 7). These values are based on other references (Cutter et al. 2000; Azar and Rain 2007; Hegglin and Huggel 2008), but were adapted to our case study region.

Age structure data for Ibagué were not available with accurate resolution. Instead, we used SISBEN data that provide an indicator of the socio-economic level of the population (see Sect. 3). The reason to use socio-economic status data as an indicator for social

Table 6 Population densities in the locations under investigation

Location	Total population	Population per m^2 of parcel/block area (mean)	Population per parcel or block (mean)	Number of parcels or blocks inhabited (total)
Juntas	207	0.020	2.9	72 (74)
Villa Restrepo	198	0.007	2.6	75 (105)
Pico de Oro	83	0.009	3.3	25 (30)
Pastales	266	0.017	2.6	102 (105)
Llanitos	317	0.035	4.2	74 (75)
Ibagué district 1	22,870	0.014	93	245
Ibagué district 11	37,566	0.034	155	242
Ibagué district 12	41,869	0.040	124	338
Ibagué district 13	18,084	0.012	93	194

Total population data are based on the references in Sect. 3

vulnerability is that poor people generally suffer more from the effects of disasters than more wealthy ones (Glade 2003; Alcántara-Ayala 2002; Puente 1999 in Liu et al. 2002: Solway 1999 in Liu et al. 2002) (Table 8).

In Ibagué, we analysed vulnerability for those city districts that are potentially affected by flood and/or lahar hazards. We used the lowest (poorest) socio-economic level (level 1) of SISBEN as an indicator of poor people and high social vulnerability. As shown above, social vulnerability in the five villages refers to age structure, while in the city of Ibagué, it refers to poverty. Therefore, the levels of social vulnerability and eventually also risk between the villages and Ibagué are not directly comparable.

5.3 Standardization

When performing a multi-criteria evaluation (MCE), the input data need to be standardized from their original units to comparable units, such as a range from 0 to 1. Most often, a linear scale transformation is used (Malczewski 1999), which transforms the input values linearly into values between 0 and 1. However, this standardization method can be inappropriate when the original values include disproportionately high or low values (Castellanos Abella and van Westen 2007), which is often observed when dealing with population density data, because densities are much higher in urban than in rural areas. To avoid this problem, we used a concave curve equation as proposed by Castellanos Abella and van Westen (2007) to transform the physical vulnerability data. We set the inflection points of the curve at the median value of the original data corresponding to 0.5 in the new scale. In other words, after the standardization, half of the values are above 0.5 and half below 0.5 (Figs. 8, 9). In contrast to physical vulnerability data, social vulnerability data include no extreme values, and an adapted linear scale transformation was performed, setting the median value after the standardization at 0.5.

After these standardization procedures, all vulnerability criteria range from 0 to 1. We call the standardized values *indices* to prevent confusion with the original data. Each criterion is represented in a rasterized map layer. To calculate total vulnerability V_{tot}, the layers were summed up using the following equation:

Table 7 Age structure in the villages

Village	Children (%)	Elderly people (%)	Vulnerable people (%)	References
Juntas	28	18	45	Sarmiento et al. (2005a)
Villa Restrepo	25	24	49	Barrios Peña and Olaya Marín (2007)
	29	23	52	CORTOLIMA (2006e)
Pico de Oro	30	21	51	Sarmiento et al. (2005b)
Pastales	23	15	38	Alcaldía de Ibagué (unpublished)
	44	20	64	CORTOLIMA (2006c)
Llanitos	25	30	55	CORTOLIMA (2006b)

For Villa Restrepo, we used the value of Barrios Peña and Olaya Marín (2007); for Pastales, we used the mean value, that is 51 %

Table 8 Social structure in the districts of Ibagué

District	Population (SISBEN)	Category 1, number of people	Category 1, percentage of total (%)
1	19,234	5,510	29
11	31,593	6,867	22
12	35,212	5,679	16
13	15,209	3,928	26

Category 1 represents the poorest socio-economic population level. *Source*: SISBEN

$$V_{\mathrm{tot}} = 0.5 * V_{\mathrm{MV}} + 0.25 * V_{\mathrm{PD}} + 0.25 * V_{\mathrm{SV}} \quad (1)$$

where V_{MV} is the market value index, V_{PD} is the population density index, and V_{SV} the social vulnerability index. It should be noted that the weighting is rather a political and societal than a scientific process as it determines which components of vulnerability are more or equally important than others. Therefore, the weighting of the different vulnerability indices was discussed with several authorities of Ibagué and the Combeima valley. Maps that show the final vulnerability are provided in Fig. 10. Although not shown here (due to space limitations), our methodology allows us to disentangle the final vulnerability map if information on different aspects of vulnerability is required.

6 Risk analysis and local application

Risk was calculated by multiplying the hazard index with the vulnerability index. Consequently, risk values theoretically range from 0 (no risk) to 1 (maximum risk). In our study, maximum risk values found are 0.5 in the villages (mean: 0.094, median: 0.083, zero values are excluded) and 0.61 in Ibagué (mean and median: 0.16, zero values are excluded). For authorities, risk classes are more convenient than numerical values. To determine class breaks, we used the natural break method, which sets class boundaries where there are significant jumps in the data values (ESRI 2011).

Results show that except for the centre of Pastales and most parts of Juntas, all parcels of the five villages are at risk (Fig. 11). Generally, the closer the parcel is to the river, the

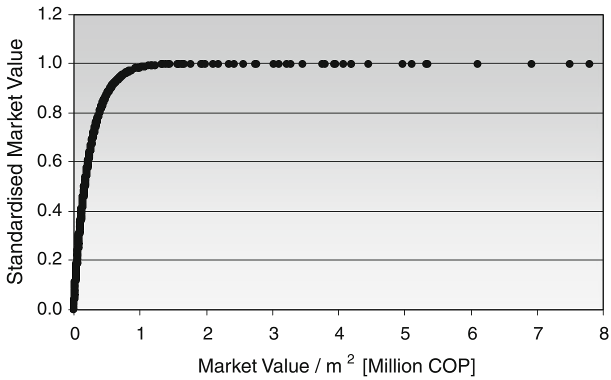

Fig. 8 Standardization curve of market value data showing the original values on the *horizontal axis* and the standardized values on the *vertical axis*, respectively

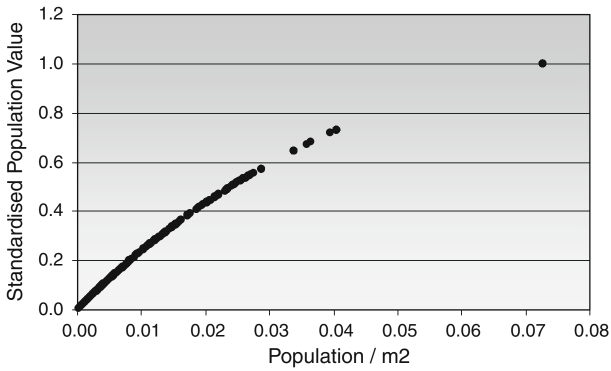

Fig. 9 Standardization curve of population data, showing the original values on the *horizontal axis* and the standardized values on the *vertical axis*, respectively

higher the risk. This can be seen in Villa Restrepo and even more so in Pastales. However, parcels falling in the very high-risk class are not found to cluster at specific sites but rather occur in every village and in every part of the villages. Except for Juntas, which mainly lies far above the river, no village is clearly at lower risk than the others. Due to the fan topography of Ibagué with much of the city located more than 100 m above the level of the Combeima river, risks related to floods and lahars are restricted to a ~500-m-wide band along the Combeima river. Within this band, many blocks show substantial levels of risk (Fig. 11). Other than in the villages, there is a concentration of medium to high-risk blocks in Ibagué, namely on the orographic right side of the Combeima river, which is an effect of both high physical and social vulnerability.

Within the perimeter of the 15 million m^3 lahar scenario, the total market value of dwelling parcels is estimated to be 120 million USD and the total population 22,000, respectively, based on our building and population data. The physical damage and the number of affected people may be much higher, because the streets and bridges in Ibagué, the agricultural land, and scattered farms are not part of our estimate. Cepeda and Murcia (1988) roughly estimated the number of people in the Combeima valley potentially prone to lahars at 50,000, yet applied lahar volumes of up to 27 million m^3 and did not specify their estimation method. Independent of the exact number of affected people, a 15 million m^3 lahar could result in a disaster of the dimension of the 1985 Armero catastrophe, which caused damage of around 250 million USD and brought death to 23,000 people

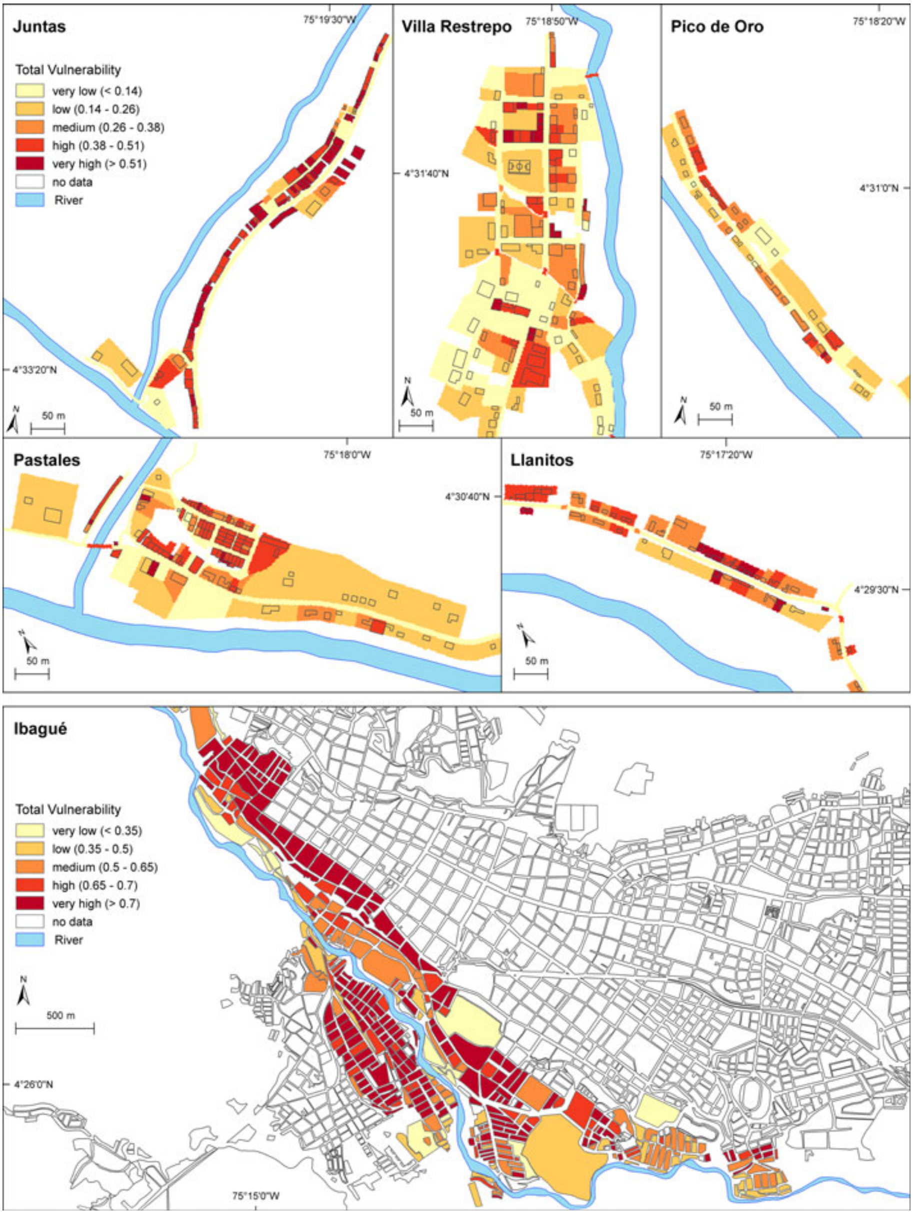

Fig. 10 Vulnerability maps. In the five villages (*top* and *centre*), vulnerability includes market values of dwelling parcels, population density, and age structure data. In Ibagué (*bottom*), vulnerability includes market values of dwelling parcels, population density, and poverty data. Classes are based on natural breaks within the data

(Pierson et al. 1990). Assuming a return period of 1000 years for the 15 million m^3 lahar scenario, the annual probability of occurrence is 0.1 %. For a person living 25 years in the study area, the personal probability to get affected by a lahar of this size is 2.47 %, which is comparable to the probability of rolling a six twice in a row (2.77 %).

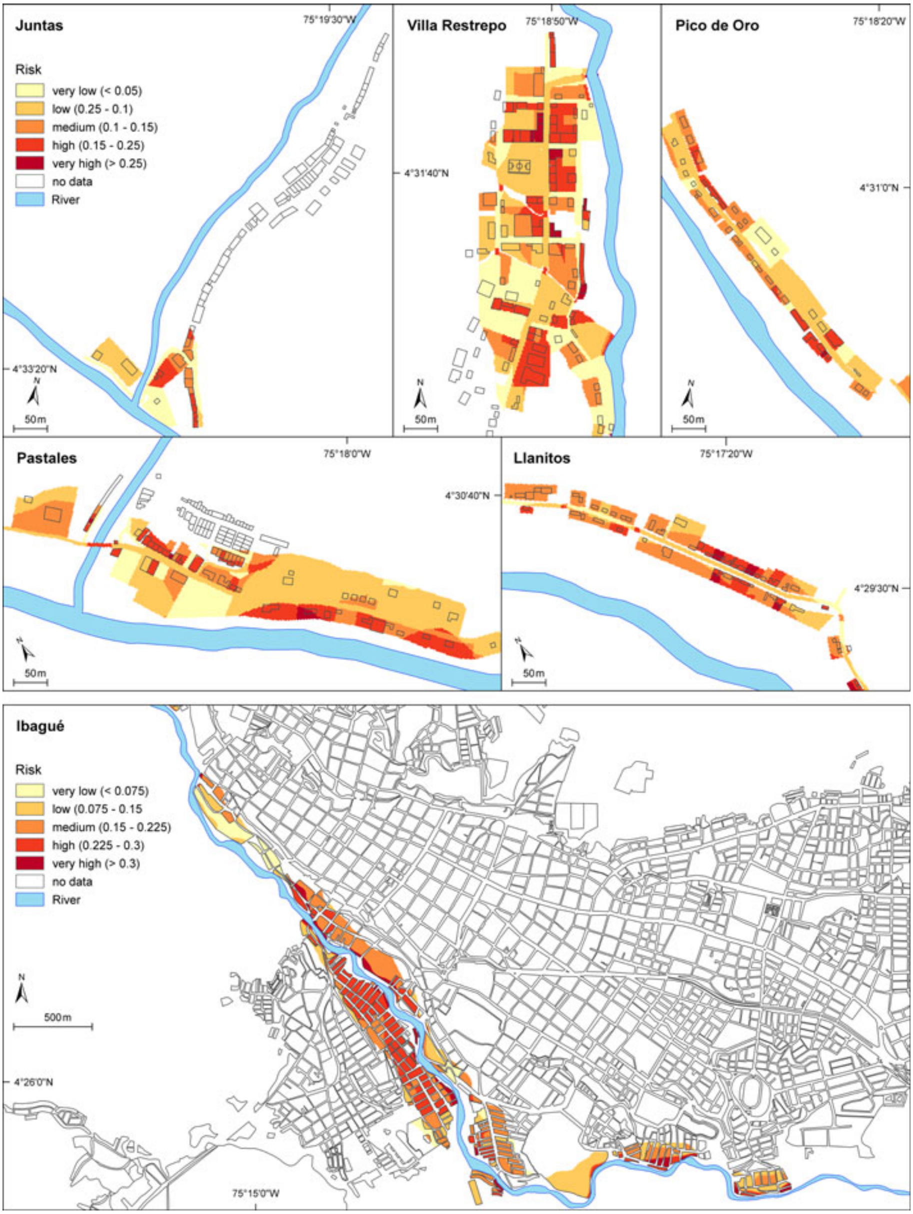

Fig. 11 Risk maps as the product of the hazard and the vulnerability maps. Classes are based on natural breaks within the data. Floods from tributaries and their impacts are not considered

7 Discussion

The main objectives of this study were twofold: (1) development of a method for a analysis of risks related to two hazardous processes (lahars and floods), which integrates physical as well as social components of vulnerability and supports risk reduction and management efforts; (2) application of the method to the Combeima valley and Ibagué to produce risk maps useful for risk reduction efforts in this region.

7.1 Method

The presented methodology analyses the risks of lahars and floods and integrates physical and social aspects of vulnerability on dwelling parcel/block level. The combination of physical and social vulnerability is widely postulated in current risk research (Cutter 1996; Hufschmidt et al. 2005; Birkmann and von Teichman 2010) but is still rather rare on this level of spatial resolution and quantification (IPCC 2012). The presented framework clearly expresses hazard, vulnerability, and risk within a range from 0 to 1. Partially subjective but fully reproducible and transparent definitions have to be made regarding the standardization and weighting of hazard and vulnerability. A fully objective analysis of risk is barely feasible (Uzielli et al. 2008), because the process of weighting vulnerabilities involves political and societal decisions.

One of the crucial problems of risk analysis is the availability, reliability, and resolution of data. Funds for additional data acquisition are typically limited or are not available at all. Our method is based on a number of indicators that require spatial data but may be adjusted to contexts with different data availability. Here, we used existing official government data, complemented by necessary field surveys. The resulting risk analysis provides an overview of risks on a local to regional scale, highlighting areas of high risk. Those areas identified should be further studied using more detailed surveys and data.

For instance, significant improvement of the hazard analysis can be expected from a higher resolution of the DEM applied for hazard modelling, because even relatively small topographic features such as terraces can influence the flow path and the perimeter of inundated areas (Stevens et al. 2002; Huggel et al. 2008). More extensive geomorphological field work may contribute to refine lahar (and flood) modelling, for instance with respect to sediment entrainment or flow rheology, but scenarios will continue to bear some uncertainty.

To evaluate our hazard mapping results, we compared them to the detailed hazard map (scale 1:2,000) performed by Thouret and Laforge (1994) for floods and lahars for Ibagué. Direct comparison of lahar hazard maps reveals a high degree of consistency among the two methods (Fig. 12). Specifically, we compare our 15 million m^3 lahar scenario with a scenario of 10–15 % melting (in water equivalent) of the ice cap, studied by Thouret and Laforge (1994) that is expected to represent a similar volume as in our scenario (Cepeda and Murcia 1988). The high degree of consistency between the two results is remarkable, given the somewhat different scale and the independence of the two methods, and increases the confidence in our model results.

LAHARZ is an easy-to-apply model, can generate useful results, and has been used in a large number of lahar studies, but it also has several limitations, for instance a rigid delimitation of erosion and deposition that is a poor approximation of physical lahar processes. The application of more complex, dynamic flood and lahar models may be recommendable for further details on flow characteristics such as flow velocities (e.g. Fagents and Baloga 2006). It should be considered, however, that more complex models require (1) input parameters that may be difficult or time/cost-intensive to acquire and (2) extensive calibration procedures. Furthermore, it should be stressed in this context that a scenario, such as used for the hazard assessment, is one possible outcome in the future among several other ones that are possible. We designed the scenarios in a way that they are robust and can encompass a broad range of possible outcomes, though not every one.

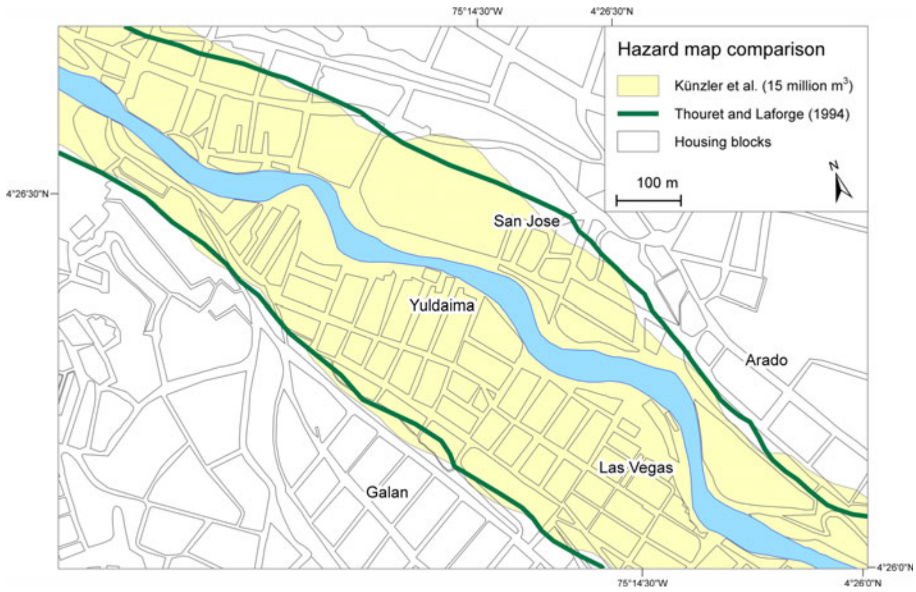

Fig. 12 Comparison of the 15 million m^3 lahar scenario and the perimeter presented by Thouret and Laforge (1994) for a melting of 10 to 15 % of the ice cap, around Yuldaima quarter, Ibagué

Our hazard index scheme (Fig. 5) is based on magnitude as well as return period and allows for the standardization of flood and lahar hazards. Comparable standardization schemes are not particularly widespread in literature but very useful when considering multiple hazard processes. Moreover, applying the same range to hazard, vulnerability, and risk (0–1) makes the method clear and transparent, which is important in any hazard and risk assessment (Raetzo et al. 2002).

There is room for improvement regarding the assessment of vulnerability. In this study, it was possible to identify areas with different densities of population and dwellings, but some uncertainties remain due to the limitations regarding the quality and the resolution of data. Better social and population data would be helpful as already mentioned in former studies (e.g. Hegglin and Huggel 2008; Cutter et al. 2003), but is often not available at the desired spatial scales. In this study, we had to use aggregated social and population data to calculate vulnerability, being aware that aggregation ignores differential vulnerability within the unit of analysis (Bara 2010). Theoretical concepts suggest consideration of several other indicators of social vulnerability. In case data availability is high, or resources are available for detailed surveys, additional indicators of social vulnerability could relatively easily be integrated into our methodological concept.

Vulnerability in our analysis depends on age structure in the villages and on poverty in the city of Ibagué. Consequently, a direct comparison of vulnerability is not possible. Whereas we consider poverty a rather strong indicator for social vulnerability, age structure is only one among several elements of social vulnerability. Future studies should necessarily be based on additional indicators and try to include risk perception as for example done by Thouret and Laforge (1994) for 120 households in Ibagué. In fact, recent research on risk perceptions related to volcano hazards emphasizes the importance of understanding the social, cultural and economic contexts as a factor determining how people respond to risks (Gaillard and Dibben 2008; Degg and Chester 2005; Gavilanes-

Ruiz et al. 2009). Decisions and behaviour that may first appear irrational can emerge as rational and explicable, once the social and economic contexts are better explored (Gaillard 2008). Community involvement and trust in institutions have also been identified as important determinants of the level of preparedness (Paton et al. 2008), a finding that has recently also been confirmed for the population centres of the Combeima valley (M. Thomas, pers. communication).

On the methodological level, more research is needed which factors of social vulnerability can be integrated in a risk analysis on household level, and how to combine them with quantitative data of the physical hazard (Tapsell et al. 2010). In fact, while there is wide agreement in literature that social aspects decisively influence the vulnerability of people (e.g. Dikau and Weichselgartner 2005; Hufschmidt et al. 2005; Alcántara-Ayala 2002; Cutter et al. 2000; Dibben and Chester 1999), the most important factors and their integration into (quantitative) risk analysis are much less clear (Kuhlicke et al. 2011). Further research is also required with respect to the visualisation of risk and its communication to decision makers (Castellanos Abella and van Westen 2007).

Moreover, risk is not static and many input data change with time (for instance glacier shrinkage, changes in geomorphology and vulnerability). A regular update of the risk maps would therefore be desirable (Fekete 2009; Papathoma-Köhle et al. 2010).

Weighting and standardization of hazard and vulnerability indicators is a powerful lever to steer the final risk results. Despite this importance, there has been little research into methods of weighting and standardization of indicators for disaster risk analysis so far. Castellanos Abella and van Westen (2007) applied multi-criteria evaluation techniques, while Komac (2006) and Yoshimatsu and Abe (2006) applied analytical hierarchical process methods, yet restricted to landslide susceptibility. The process of weighting vulnerability indicators involves the political and societal level and thus goes beyond scientific responsibility and thus should be undertaken in discussion with public authorities.

7.2 Results and implications

Results suggest an important need for risk prevention and mitigation in the Combeima region. The most effective way to reduce the risk would be the relocation of the population at risk. However, relocation often is not a feasible political and social option (Liu et al. 2002), and people might be reluctant to be resettled (Gavilanes-Ruiz et al. 2009). Preventive land-use planning, therefore, should be at the forefront, for example the construction of further settlements that are close to the river must be avoided in the villages as well as in Ibagué.

In addition, we consider early-warning systems a most effective short-term measure to avoid casualties. Together with the Swiss Agency for Development and Cooperation and within a risk reduction project, local and regional authorities recently started implementing an early-warning system whose design is described in Huggel et al. (2010). Three rainfall gauging stations were installed in 2008, each of which includes rainfall measuring equipment and a geophone. In 2009, a real-time discharge station was installed at the Combeima close to Villa Restrepo. Further equipment installed higher on the volcano’s slopes might be necessary for more effective lahar warning. Early-warning systems and education campaigns are important elements of risk reduction measures and will greatly help reducing the number of affected people, but cannot significantly reduce damage to infrastructure damage. Structural protection measures may eventually be a way to reduce physical vulnerabilities at specific critical locations.

The hazard, vulnerability, and risk maps described in this study entered such risk reduction efforts by providing relevant information to the local and regional authorities. While the local and regional disaster prevention agencies have been well involved in this study, the planning level of the city of Ibagué and the province of Tolima have not yet sufficiently considered risk aspects for land-use planning. Reasons are, for instance, economic pressure, political forces, or other priorities.

8 Conclusion

The method of integrating information from hazard and vulnerability into a risk analysis, as presented here, allows for an identification and categorization of risks from floods and lahars at reasonable cost. The information and especially the maps were highly appreciated by the responsible local authorities and served for risk reduction planning. Application of the method, possibly in an adjusted way, to other regions is considered feasible, and the type of information generated is particularly useful in areas where no risk information at all exists.

However, there is also room for improvement, both on data and methodological levels. A higher spatial resolution of DEM and social data could improve the spatial accuracy of the results. Methodologically, the consideration of social, cultural, economic, or political vulnerability for the overall risk analysis should be further developed, as widely postulated but not yet sufficiently put into practice. The harmonization of approaches from physical-engineering and social science remains an important challenge.

The hazard index as developed in this study represents a framework for a reasonable assessment of flood and lahar hazards. The risk analysis for the Combeima region allows for identification of areas with different degrees of risk, an important input for further risk reduction measures. It also provides estimates of damage, with the high-hazard scenario (lahar with a volume of 15 million m^3) potentially resulting in a directly exposed population exceeding 20,000, and damages of 120 million USD as a minimum estimate. In general, the risk analysis has shown that almost all villages of the Combeima and extensive areas of Ibagué are exposed to risks from floods and lahars. We have not found any distinct risk hot-spots, rather high-risk areas prevail in many parts of Ibagué and every village. Landslides and debris flows from tributary channels further increase the risks but were not considered here.

Lahar scenarios should be regularly revised as the glaciers on Tolima volcano undergo dynamic changes (i.e. shrinkage). Vulnerability, on the other hand, is not static either and should regularly be revised as well.

Furthermore, risk reduction programmes have been initiated within the framework of international collaboration. Adequate land-use planning would be among the most effective risk reduction measures but is difficult to implement due to political, economical, and social constraints. Early-warning systems show more immediate success as recent experiences show but need to be accompanied by education, capacity, and confidence-building efforts. Sustainable penetration of risk reduction consideration and efforts into the political decision-making process remains one of the main challenges.

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