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Regional flood susceptibility analysis in mountainous areas through the use of morphometric and land cover indicators

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Abstract

A classification of susceptibility to flooding of 106 mountain watersheds was carried out in Bogotá (Colombia) through the use of an index composed of a morphometric indicator and a land cover indicator. Susceptibility was considered to increase with flashiness and the possibility of debris flows. Morphological variables recognised in literature to significantly influence flashiness and occurrence of debris flows were used to construct the morphometric indicator by applying principal component analysis. Subsequently, this indicator was compared with the results of debris flow propagation to assess its capacity in indentifying the morphological conditions of a watershed that make it able to transport debris flows. Propagation of debris flows was carried out using the Modified Single Flow Direction algorithm, following identification of source areas by applying thresholds identified in the slope-area curve of the watersheds. Results show that the morphometric variables can be grouped in four categories: size, shape, hypsometry and energy, with energy being the component that best explains the capability of a watershed to transport debris flows. However, the morphometric indicator was found to not sufficiently explain the records of past floods in the study area. Combining the morphometric indicator with land cover indicators improved the agreement, showing that even if morphometric parameters identify a high disposition to the occurrence of debris flow, improving land cover can reduce the susceptibility. On the contrary, if good morphometric conditions are present but deterioration of the land cover in the watershed takes place then the susceptibility to debris flow events increases.

1 Introduction

Appropriate recognition of hydrogeomorphic hazards in mountain areas is crucial for risk management, since it provides the basis for more detailed studies and for the development of appropriate risk management strategies (Wilford et al., 2004; Jakob and Weatherly, 2005; Welsh, 2007). Besides the identification of the flood potential, it is important to distinguish between debris-flow and non debris-flow dominated watersheds since these constitute very different hazards. Debris flow fans pose a more significant hazard than clear water fans in terms of peak discharge and percentage of debris load (Santangelo et al., 2012). The distinction between debris flow and clear water dominated watersheds therefore has significant implications for the appropriate hazard management approach (Welsh, 2007; De Scally and Owens, 2004; De Scally et al., 2010). Previous research on the identification of flood potential and areas susceptible to debris flows used quantitative methodologies such as logistic regression and discriminant analysis in addition to GIS and remote sensing technologies (De Scally and Owens, 2004; De Scally et al., 2010; Wilford et al., 2004; Rowbotham et al., 2005; Chen and Yu, 2011; Santangelo et al., 2012; Crosta and Frattini, 2004; Griffiths et al., 2004; Kostaschuk, 1986; Patton and Baker, 1976). These studies focused on the identification of basins or fan parameters to classify them according to their dominant hydrogeomorphic processes. A conclusion from these studies is that drainage basin morphology is an important control of fan processes (Crosta and Frattini, 2004) and that there are significant differences in morphometric characteristics between basins where the dominant process is debris flows and those mainly dominated by fluvial processes (Welsh, 2007). Morphometric parameters such as the basin area, Melton ratio and watershed length have been identified by several authors as reliable predictors for differentiating between debris-flow and non-debris-flow dominated watersheds and their respective fans (Welsh, 2007). However, the results of the analyses seem to be highly dependent on the geographical area where the methodology is applied and in many cases the identification of morphometric parameters requires a previous independent classification of the watersheds normally entailing stratigraphic observations, detailed field work, aerial photo analyses and calculations. The level of detail this requires may not be practicable in identifying watersheds in the extensive peri-urban areas of cities in mountain areas such as the Andean cordillera due to the limited available data as well as the sheer number of such watersheds, calling for more rapid yet reliable assessment techniques. This paper proposes a method for regional assessment of flash flood susceptibility under limited availability of data, where flash floods occur as debris flows, hyperconcentrated flows or clear water flows. The proposed index is based exclusively on information derived from digital elevation models and satellite images to overcome the limitation often found in the availability of previous geological work such as stratigraphic analysis and field work for large areas. A key aspect of the index is the discrimination between debris flow and clear water flood dominated watersheds in order to understand the level of threat that floods in the watersheds pose. The ability of morphometric variables to identify debris-flow dominated basins was tested. Morphometric variables and land cover characteristics were considered as factors that influence flood hazard, and were combined in an index that can be interpreted as the degree of susceptibility to which watersheds are prone, including spatial differentiation of the dominant type of hazard. The study area is the mountainous area surrounding the City of Bogotá (Colombia). Results of the methodology were evaluated using a comprehensive database of recorded floods.

2 Methods and data

2.1 Study area

This research focuses on the mountainous watersheds surrounding the city of Bogotá, the capital and economic centre as well as the largest urban agglomeration of Colombia with an estimated 7.4 million inhabitants. The city is located in the Andean region (see Fig. 1). Several creeks drain the steep mountains surrounding the city, cross the urban area to finally discharge into the larger Bogotá River. In this analysis the watersheds that drain into the main stream of the Tunjuelo river basin, one of the largest tributaries of the Bogotá River, 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. 1a). These are characterised by a mountainous environment with areas ranging between 0.2 km^2 and 57 km^2. The elevation of the study area ranges between 2510 m a.s.l. and 3780 m a.s.l. and the mean annual precipitation varies from 600 mm to 1200 mm in a bimodal regime (Bernal et al., 2007).

In the study area, flooding is controlled by climate and physiography. However, land use practices and anthropogenic influences add significantly to the problem. In the southern mountains of Bogotá, which belong to the Tunjuelo river basin, the urban and industrial growth has been accelerated from the 1950's. Between 1951 and 1982, the lower basin of the Tunjuelo river was the most important area for urban development. It was settled by the poorest population of Bogotá (Osorio, 2007), and its growth has been characterised by informality and lack of planning. The most devastating floods in Bogotá have occurred in the lower Tunjuelo river basin, involving not only the main stream but also the tributary creeks where flash floods have caused human losses (DPAE, 2003a, b, c). The watersheds located in the Eastern Hills of Bogotá have different characteristics since most of the area corresponds to protected forests. However, informal urbanisation takes place in some areas. Additionally, mining has been common both in the Tunjuelo river basin and in the Eastern Hills, causing the deterioration of the environmental conditions of the watersheds.

In order to test the performance of the proposed morphometric indicator, additional to the watersheds in the study area, a sub-watershed of the Chiguaza creek in the Tunjuelo river basin (see Fig. 1a) was analysed, as well as two areas external to the study area; La Negra creek and La Chapa creek (see Fig. 1b and c). These additional watersheds were included in the analysis given the availability of records and previous studies. La Negra creek is located 67 km to the North West of Bogotá. Among several records of inundation events on the 17 November 1988 an event affected the watershed. The flow moved along La Negra creek to its confluence with the Negro River affecting an important area of the municipality of Utica (UNAL and INGEOMINAS, 2007). According to UNAL and INGEOMINAS (2007) the characteristics of this event reveal a concentration of sediment of 40 % by volume, which corresponds to the upper limit of the mud flood category according to O'Brien (2006) or debris flood according to (Wilford et al., 2004).

La Chapa creek was chosen due to the high frequency of debris flows. Chaparro (2005) notes that La Chapa creek is prone to debris flows characterised by the mobilization of granular material of varying size, ranging from boulders of several meters in diameter to sand, embedded in a liquid phase, formed by water, fine soils and air, sometimes accompanied by vegetal material. The most recent event that took place in this watershed was recorded on video, which allowed the type of flow that dominates the watershed to be confirmed.

2.2 Methodology

There are several definitions and terminology for hydrogeomorphic processes. Wilford et al. (2004) distinguishes among floods, debris floods and debris flows with sediment concentrations of 20 % and 47 % as upper limits for floods and debris floods respectively. Santangelo et al. (2012) differentiates floods, hyperconcentrated flows and debris flows as defined by Costa (1988), stating that water floods are newtonian, turbulent fluids with non-uniform concentration profiles and sediment concentrations of less than about 20 % by volume and shear strengths less than 10 $\mathrm{N\,m^{-2}}$; hyperconcentrated flows have sediment concentrations ranging from 20 to 47 % by volume and shear strengths lower than about 40 $\mathrm{N\,m^{-2}}$; and debris flows are non-Newtonian visco-plastic or dilatant fluids with laminar flow and uniform concentration profiles, with sediment concentrations ranging from 47 to 77 % by volume and shear strengths greater than about 40 $\mathrm{N\,m^{-2}}$. On the other hand, O'Brien (2006) uses the terms mudflow (non-homogeneous, non-Newtonian, transient flood events), and mud flood (sediment concentration from 20 % to 40–45 % by volume). Despite the variety of definitions, the characteristics of debris flows imply different hazard conditions from those related to clear water floods, with debris flows being potentially more destructive. The higher destructive capacity is related to a much faster flow and higher peak discharges than those of a conventional flood; as well as high erosive capacity with the ability to transport large boulders and debris in suspension and the generation of impact forces comparable to rock and snow avalanches (Welsh, 2007). With a lower sediment concentration, debris floods and hyperconcentrated flows as presented by Wilford et al. (2004) and Santangelo et al. (2012) are less hazardous, since they carry less of the large boulders responsible for impact damage in debris-flows and flow velocities are usually lower. They are, however, considered more dangerous than clear water floods of similar magnitude (Welsh, 2007). This variability in level of hazard is reflected in the proposed susceptibility index, where high values represent a higher potential for debris flow and therefore an increased hazard condition. The proposed index to represent the level of flood susceptibility at regional scale is composed of a morphometric indicator and a land cover indicator.

2.2.1 Construction of the morphometric indicator

In order to develop the morphometric indicator and identify its appropriateness, two independent approaches were followed. The first assesses morphometric parameters that have been identified in literature as important descriptors of flood potential and debris flow discriminators to construct a morphometric indicator of susceptibility to increasingly damaging flood events. The second identifies debris flow source areas and propagates the flow on a digital elevation model (DEM) in order to identify the capacity of watersheds to transport potential debris flows to their fans. A comparison between the two approaches was carried out. The two approaches are shown schematically in Fig. 2 where the main steps are shown. The main input for both approaches is a five meter resolution raster DEM constructed from contours.

In the case of the first approach, the morphometric parameters shown in Table 1 were extracted. Subsequently, these were analysed through principal component analysis to obtain the morphometric indicator. According to Takahashi (1981) and Rickenmann and Zimmermann (1993) the critical factors for debris flow occurrence are sediment availability, water input and slope gradient. While sediment availability and slope gradient refer to the general disposition, the water input from precipitation and snow melt acts as a triggering factor (Kappes et al., 2011). The water input is strongly related to the upslope area in which precipitation accumulates. The slope is critical due to its influence on the shear strength of the soil and debris. Sanchez-Marre et al. (2008) note that prerequisite conditions for debris flows include an abundant source of unconsolidated fine-grained rock and soil debris, steep slopes, a large but intermittent source of moisture (rainfall or snowmelt) and sparse vegetation. Differentiation of debris flow watersheds or fans from those dominated by clearwater floods has been carried out by several authors, finding that morphometric variables are very valuable as discriminators of processes in watersheds (De Scally and Owens, 2004; De Scally et al., 2010; Wilford et al., 2004; Rowbotham et al., 2005; Chen and Yu, 2011; Santangelo et al., 2012; Crosta and Frattini, 2004; Griffiths et al., 2004; Kostaschuk, 1986; Patton and Baker, 1976). On the other hand, research on the relationships between watershed characteristics and peak-flood and flashiness has contributed to identify morphometric variables that can help to describe the characteristics of the hydrologic response of a watershed (Patton, 1988). Table 1 summarizes the morphometric variables that have been identified in literature as appropriate discriminators of processes and descriptors of the hydrologic response of watersheds and that were chosen for the analysis. The parameters that are most commonly found in literature as important discriminators of hydrogeomorphic processes are the area, the slope and the Melton ratio. However, other parameters such as those derived from the hypsometric curve and the average of the multiresolution index (Gallant, 2003) have also been included given their importance in the description of the evolution and erosion processes of watersheds in the case of the former and the description of the erosion areas in the case of the latter.

The hypsometric curve and the hypsometric integral are non-dimensional measures of the proportion of the catchment above a given elevation (Willgoose and Hancock, 1998). The hypsometric curve describes the landmass distribution and thus the potential energy distribution within the basin above its base (Luo and Harlin, 2003). This curve can be seen as an exceedence distribution of normalised elevation where the probability of exceedence is determined by the portion of the basin area that lies above the specified elevation (Huang and Niemann, 2008). The hypsometric integral is defined as the area below the hypsometric curve. Values near to 1 in the hypsometric integral indicate a state of youth and are typical of convex curves. Nevertheless, mature s-shaped hypsometric curves can present a great variety of shapes, but have the same hypsometric integral value (Pérez-Peña et al., 2009). In order to analyse the hypsometric properties of the watersheds, the procedure described by Harlin (1978) was used: the hypsometric curve was treated as a cumulative distribution function. The second, third and fourth moments were derived about the centroids, yielding measures of skewness and kurtosis for the hypsometric curves, which are represented by a continuous third order polynomial function.

The multiresolution valley bottom flatness index (MRI) is obtained through a classification algorithm 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 a single index. The MRI utilizes the flatness and lowness characteristics of valley bottoms. Flatness is measured by the inverse of the slope, and lowness is measured by a ranking of the elevation with respect to the surrounding area. The two measures, both scaled to the range 0 to 1, are combined by multiplication and can be interpreted as membership functions of fuzzy sets (Gallant, 2003). The morphometric indicator was calculated for two watersheds external to the study area (La Negra creek and La Chapa) as well as for the sub-watershed of Chiguaza creek in the study area where a debris flow event was recorded.

Several hypotheses have been formulated to explain mobilisation of debris flows and this aspect represents an active research field. The triggering mechanisms and the causal relationships are, however, still partially unknown (Sanchez-Marre et al., 2008). Approaches for the identification of debris source areas include the use of credal networks (Antonucci et al., 2007), the use of indices for predisposition factors to assess debris-flow initiation hazard (Bonnet-Staub, 2000), empirical relationships (Baumann and Wick, 2011; Horton and Jaboyedoff, 2008; Blahut et al., 2010), the Melton's Ruggedness Number (Rengifo, 2012) and the use of the slope vs. area diagram as a topographic signature of debris flow dominated channels (Santos, 2006). Two of these methodologies to identify potential debris flow initiation points will be used in this paper for approach 2. The first is based on the analysis of the break in the slope vs. drainage area relationship, while the second uses an empirically determined critical condition in this relationship (Horton and Jaboyedoff, 2008). In both cases, the debris flow propagation areas were obtained through a propagation algorithm by considering two angles of reach (ratio between the elevation difference and length from the debris flow initiation point to the downstream extent of the debris flow runout) (Horton and Jaboyedoff, 2008; Kappes et al., 2011). The binary result of the propagation reaching or not reaching the fan of each watershed was used to assess the skill of the morphometric indicator to detect dangerous conditions in the watersheds.

The slope–area diagram is the relationship between the slope at a point vs. the area draining through that point. It quantifies the local topographic gradient as a function of drainage area. Several authors have found a change in the power-law relationship (or a scaling break) in slope–area data from DEMs at the point that the valley slope ceases to change below a certain drainage area. This has been inferred to represent a transition to hillslope processes and has been interpreted as the topographic signature for debris flow valley incision (Stock and Dietrich, 2003; Montgomery and Foufoula-Georgiou, 1993; Seidl and Dietrich, 1993). The same conclusion was made by Tucker and Bras (1998) explaining that different processes have an impact on the slope–area relationship, suggesting the possibility that slope–area data may be used to discriminate between different geomorphic process regimes. Two distinct regions of the slope–area diagram are typically observed. Small catchment areas are dominated by rainsplash, interrill erosion, soil creep or other erosive processes that tend to round or smooth the landscape. As the catchment area becomes larger, a break in gradient of the curve occurs. This is where slope decreases as catchment area increases. This region of the catchment is dominated by fluvial erosive processes that tend to incise the landscape (Hancock, 2005). Santos (2006) presents topographic and field evidence of the topographic signature of debris flow dominated channels with data from the Cantabrian Cordillera in Spain and explores the potential application of this topographic signature as a criterion for the recognition of debris flow prone channels at a regional scale and examines its use for hazard analysis. Santos (2006) found that the inflection between the colluvial and alluvial domains in the slope–area relationship was defined by slopes between 0.1 and 0.7, and contributing areas ranging from 1 to 10 km^2 in the Cantabrian Cordillera, Spain; Montgomery and Foufoula-Georgiou (1993) found that the averaged plot for the South Fork Smith River, California reveals an inflection at a drainage area of approximately 1 km^2 corresponding to local slopes of about 0.2 to 0.3, while in the Tennessee Valley the inflection was identified at a drainage area of about 0.1 km^2; Seidl and Dietrich (1993) report a change in the slope-area properties of tributary junctions derived from topographic maps of the Oregon Coast Range at gradients of about 20 % and argue that this transition reflects a change in the dominant erosional mechanism from debris flow to fluvial processes. In contrast Stock and Dietrich (2003) report that field observations and map analysis demonstrate that debris flows that occur in landscapes steep enough to produce mass failures both erode bedrock and have a topographic signature in the form of a curvature in the slope–area diagram above a slope of 3 to 10 %. The slope–area curve was constructed for two regions of the study area corresponding to the Tunjuelo river basin and to the Eastern Hills of Bogotá. The break in the slope–area diagram was inferred visually, in order to determine a threshold.

The second method that was applied to identify debris flow sources is the procedure proposed by Horton and Jaboyedoff (2008). This applies criteria based on area, slope, curvature, hydrology, lithology and land cover. The slope criterion, is based in the relationship between slope and drainage area shown in Eqs. (1) and (2), which were built on the observations made by Rickenmann and Zimmermann (1993).

$$\mathrm{Tan}\beta_{\mathrm{lim}} = 0.31 S_{\mathrm{UA}}^{-0.15} \quad \text{if } S_{\mathrm{UA}} < 2.5\,\mathrm{km}^2 \tag{1}$$

$$\mathrm{Tan}\beta_{\mathrm{lim}} = 0.26 \quad \text{if } S_{\mathrm{UA}} \geq 2.5\,\mathrm{km}^2 \tag{2}$$

Where β_{lim} is the threshold slope in degrees and S_{UA} is the upstream area in km^2. In the method by Horton and Jaboyedoff (2008) every point located above the limits defined by Eqs. (1) and (2) is considered as critical. In the application of the method in Argentina (Baumann and Wick, 2011), the equations were bounded between 15° and 40° since in the observations made by Rickenmann and Zimmermann (1993) in Switzerland all the triggering areas slope angles were below 40° and contributing areas inferior to 1 ha were not considered as potential sources. Thus, the parameters used for detection of triggering areas are slopes in the range of 15–40°, contributing areas superior to 1 ha and plane curvatures inferior to $-0.01/200\,\mathrm{m}^{-1}$ under the condition that the point is located above the limit defined by the curve of extreme events (see Eqs. (1) and (2) and Fig. 5).

Using the threshold obtained from the analysis of the slope–area curve together with the criteria of curvature and minimum drainage area as proposed by Horton and Jaboyedoff (2008) initiation points were identified in the study area. As a second method, the threshold of extreme events was used as a criterion for slope and area and in addition the minimum area and curvature were used as recommended by Horton and Jaboyedoff (2008). The Modified single-flow-direction (MSF) model (Huggel and Kääb, 2003; Hengl and Reuter, 2009) was used to identify the areas that potentially could be affected by debris flows for the two groups of initiation points. The MSF is based on the single flow direction (D8) algorithm and other standard functionalities of ArcInfo/ArcGIS to account for flow spreading allowing the flow to divert from the steepest descent path by as much as 45° on both sides. The only required inputs are the source areas and a DEM. For a detailed explanation on the Modified Single Flow Direction (MSF) algorithm see Hengl and Reuter (2009).

As a stopping condition the MSF algorithm uses the angle of reach. The trajectory component of the MSF model usually provides the potential maximum inundation zones of a mass-movement event. Thus, it indicates which areas are more or less likely to be affected. However, the runout distance should also be based on a maximum. A reasonable H/L ratio has to be evaluated on the basis of empirical data for the type of mass movement that is being modelled. Several efforts have been made to develop relationships to estimate the angle of reach mainly using the volume of the debris flow. The minimum angle of reach that has been observed is 6.5° (ratio $H/L = 0.11$)

(Prochaska et al., 2008) and the highest and more repetitive is 11° (ratio $H/L = 0.19$) (Rickenmann, 1999; Huggel and Kääb, 2003; Rickenmann and Zimmermann, 1993; Kappes et al., 2011). The two angles will be used to test the sensitivity of the results but, larger and more fluid debris flows may show lower H/L ratios and consequently a larger flow reach. Watersheds where the propagation area reaches the mouth of the drainage area using a ratio H/L of 0.19, are classified as debris flow dominated and labeled "debris flow $H/L = 0.19$". Watersheds where the propagation reaches the mouth for a ratio H/L of 0.11, will be considered debris flow dominated as well, albeit with a more fluid flow. These are labeled "debris flow $H/L = 0.11$". In this study no distinction between hyperconcentrated flows and clearwater floods is made. Therefore, watersheds where the propagation area does not extend to the mouth of the drainage area will be classified as clearwater flood dominated. A comparison of results of the morphometric analysis is carried out, using the results obtained in the study area, two external watersheds and a subwatershed of Chiguaza creek in the study area where the record of events allows a clear classification of the dominant processes.

2.2.2 Construction of the land cover indicator

The land cover indicator was constructed by analyzing the characteristic land cover of each watershed, which was obtained from the classification of a Landsat image taken in 2001. The classification identified areas covered by forests, grass, paramo vegetation[1], urban soil and water. From the land cover composition of each watershed a qualitative condition was derived.

The natural susceptibility of a catchment to debris flow hazards due to geological, morphological and climatic predispositions can be enhanced by human activities and the effects of land use changes (Koscielny, 2008). In order to include this influence in the susceptibility analysis, the percentage of vegetation cover, urban area and bare soil is used to qualify the state of the watersheds. Vegetation cover has been recognized

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[1] Paramo is an alpine tundra ecosystem unique to the Andean Cordillera.

as one of the factors related to frequency of debris flows (Jakob, 1996). Forests reduce hydrogeomorphic hazards since they retain organic and inorganic material; contain the transport of mobilized material reducing the extent of destruction; intercept precipitation; and the stems of trees reduce the areas disturbed by snow avalanches, rockfalls, floods, debris floods and debris flows (Sakals and Innes, 2006). Runoff can be increased by deforestation, soil properties degradation and impervious surfaces construction (Koscielny, 2008) as a result of urbanization. Likewise, erosion processes and slope instabilities can occur (Koscielny, 2008). The percentage of bare soil represents areas prone to erosion and normally associated with quarries that can provide a supply of sediment. According to Schueler (1995) stream degradation occurs at approximately 10–20 % total impervious area. The increase in frequency and severity of floods due to imperviousness produces an increase in stream cross-sectional area. This occurs as a response of the stream accommodating higher flows through widening of the stream banks, downcutting of the stream bed or both. The channel instability triggers streambank erosion and habitat degradation. With respect to flood magnitude, this can be increased significantly by percentages of impervious cover larger than 10 %. Hollis (1975) found that peak flows with recurrence intervals of 2 yr increased by factors of two, three, and five with 10, 15 and 30 % impervious development. A threshold of 15 % was used to consider a high condition of urbanization of the watersheds and therefore a high degree of degradation. In order to consider the degree of degradation related to bare soil, normally related to quarries in the study area, a threshold of 10 % was used.

2.2.3 Construction of a composite susceptibility index and validation of results

The resulting indicators of land cover and morphometry were combined using a matrix that allows classification of the catchments into high, medium and low susceptibility. This matrix is shown in Fig. 3. According to the matrix both indicators are weighted equally. A comparison of the results was carried out using the available records of the occurrence of flood events in the area.

3 Results

3.1 Estimation of the morphometric indicator for the study area

The variables in Table 2 were calculated based on the DEM and principal component analysis was applied. From the Scree tests carried out on the eigen values obtained from the principal component analysis the amount of principal components to be used were found to be 4. These first four principal components account for 85 % of the variance in the data. The results of the principal component analysis applying a varimax rotation are shown in Table 2. From the analysis 4 groups of variables could be identified related to the size (inversely proportional to area), shape (proportional to circularity), hypsometry (proportional to hypsometric integral) and slope (proportional to the Melton number). Using the factor loadings obtained from the first four principal component analysis and scaling them to unity, the following equations were obtained:

$$P_{\text{size}} = 0.21L_{\text{Str}} + 0.22P + 0.20A + 0.22L_{\text{wshd}} + 0.16W_{\text{wshd}} \tag{3}$$

$$P_{\text{shape}} = 0.21\text{SF} + 0.23C + 0.22E + 0.22\text{LW} + 0.11\text{DrD} \tag{4}$$

$$P_{\text{hypso}} = 0.27\text{Hs} + 0.23\text{Hi} + 0.23\text{Hk} + 0.22\text{DHs} + 0.04\text{DHk} \tag{5}$$

$$P_{\text{energy}} = 0.12\text{StrS} + 0.24S + 0.23R_{\text{Ra}} + 0.16M + 0.25\text{MRIm} \tag{6}$$

The transformation of the variables in the analysis was made in such a way that the higher the value of the component the higher the flashiness or debris flow susceptibility. From the variability explained by each principal component, the morphometric indicator would be:

$$P_{\text{morp}} = 0.28P_{\text{shape}} + 0.20P_{\text{hypso}} + 0.22P_{\text{energy}} + 0.30P_{\text{size}} \tag{7}$$

Figure 4 shows, the distribution of the morphometric indicator against the classification of the catchments according to the angle of reach. A clear differentiation can be seen for watersheds classified as 0.19D (able to propagate debris flows to their fans with a reach angle of 0.19), with the lower quartile located above the interquartile ranges of the other two classifications. However, the differentiation between watersheds classified as 0.11D (able to propagate debris flows to their fans with a reach angle of 0.11) and clear water watersheds (C) is less clear. Even if the lower and upper quartiles of the 0.11D watersheds are higher, the median value is smaller than the C watersheds. From this result, a qualitative subdivision into categories was made on the basis of the indicator. Low values from 0 to 0.35 correspond to watersheds unable to propagate debris flows to their fans according to morphology, medium values from 0.35 to 0.61 correspond to watersheds where a propagation is possible with a reach angle of 0.11 and high values from 0.61 to 1 correspond to watersheds that can propagate debris flows with an angle of reach of 0.19. Higher values of the indicator involve small area high energy watersheds with shapes that contribute to flashiness and hypsometric characteristics that imply erosive processes. The spatial distribution of the indicator is shown in Fig. 6a. High values of the indicator are concentrated in the watersheds located in the north east of the city. This behaviour is in agreement with the characteristics of the slope-area diagram shown in Fig. 5, where on average the watersheds in the Eastern Hills have higher local slope for a given area than in the Tunjuelo Basin watersheds. This condition reflects a difference in energy.

3.2 Classification of watersheds according to the debris flows propagation capacity

The slope–area relationship for the two regions of the study area (Tunjuelo basin and Eastern Hills) and the two external comparative watersheds (Negra creek and La Chapa creek) are shown in Fig. 5. This figure shows the log slope vs. log area for each pixel in the watershed areas. To increase readability the value of the slope is averaged in bins of 0.2 log of the drainage area. The black line corresponds to the curve of extreme events given by Eqs. (1) and (2). For the Tunjuelo, Eastern Hills and La Negra watersheds the break in the graph is observed at approximately 0.1 km^2 for slopes between 0.12 and 0.22. This is in the range of the values found by other authors

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for transition from debris flows to alluvial processes (Santos, 2006; Montgomery and Foufoula-Georgiou, 1993; Seidl and Dietrich, 1993). The points that belong to the La Chapa watershed do not allow the identification of a threshold. The drainage area of this watershed is only 7 km^2 which makes the identification of the break difficult. Despite the significant scatter of the values, the slope–area points of La Chapa creek are located above the points of the other watersheds. This means that on average, the slope in this watershed is higher for a given drainage area than for the other considered watersheds. Regarding the comparison of the points with the threshold of extreme events defined by Horton and Jaboyedoff (2008), the slope–area points of La Chapa watershed are located close and above the threshold for areas from 0.02 to 10 km^2. None of the other watersheds reach the threshold of extreme events, although, the points of the La Negra watershed are close to the threshold for areas between 2 and 10 km^2. The points of the Tunjuelo river basin, in general, lie lower than the points of the other watersheds and are thus more distant from the threshold of extreme events. This result is of high importance given that La Chapa creek has a confirmed debris flow dominance, followed by La Negra creek where concentrations in the transition from hyperconcentrated flows and debris flows have been identified. The differences in the threshold of extreme events and the location of the slope–area points belonging to each watershed imply that applying the threshold of extreme events reduces the amount of initiation points in comparison with the use of the threshold obtained from the slope–area relationship for dominance of debris flow processes. It is important to highlight that the points correspond to values of local slope averaged in a range of area, therefore, even in the case of the Tunjuelo river basin individual points that meet the extreme event criteria can be identified. However, the amount is less than in the case of the other watersheds. The propagation for initiation points that meet the slope–area thresholds was calculated using the MFS algorithm. However, this appears to overestimate the number of debris flow dominated watersheds. The propagation was recalculated using only the points above the curve of extreme events. Figure 6b shows the resulting propagation areas for different angles of reach. The corresponding classification of the watersheds is shown in Fig. 6c depending on whether or not the lowest point of the watershed is reached by the propagation areas according to the angle of reach condition. The classification shown in figure Fig. 6c agrees fairly well with the classification obtained from the morphometric indicator shown in Fig. 6a as explained in Sect. 3.1.

3.3 Land cover indicator

The three factors used to qualify the state of the watersheds (percentage of vegetation cover, percentage of urban area and percentage of bare soil) are shown in the ternary plot in Fig. 7a, where five areas were identified. As explained in Sect. 2.2.2 limits for intensive degradation of the watershed were established taking into account the percentage of vegetation cover and bare soil cover (15 % and 10 % respectively) an additional limit was introduced in the ternary plot of 50 % of vegetation cover that delimits area D in Fig. 7a, which represents watersheds with low urban use but high bare soil with low vegetation cover. Watersheds corresponding to zones C, D and E in Fig. 7a were grouped into watersheds in poor condition, watersheds in zone B correspond to fair condition and watersheds in zone A to good condition. The position of the dots in the ternary plot represents the conditions of the watersheds of the study area. Most of the dots are located in zone A. However, highly urbanized watersheds with poor vegetation cover and bare soil can be identified. The spatial distribution of these watersheds can be observed in Fig. 7b where a critical area can be localized in the lower part of the Tunjuelo river basin.

3.4 Combination of indicators to obtain a final susceptibility index and comparison of results

Figure 8 shows the resulting classification of the watersheds applying the matrix shown in Fig. 3. In this, observed occurrence of floods was superimposed on the susceptibility classification where each dot represents a recorded flood. The spatial distribution of the flood events clearly concentrates in the watersheds located in the lower basin of the Tunjuelo river where there is a cluster of watersheds classified as medium and high susceptibility. Flood records are less frequent in the Eastern Hills and non existing in the upper Tunjuelo river basin which may be due to the low density of population in this area. Unfortunately the information of the flood records is very limited and there are no data about extent, depth, duration and flow characteristics with only a few exceptions. Where it was identified, the flow type (observed flow type) was assigned to the corresponding watershed. The observed flow type was assigned according to the flow type observed at the mouth of the watersheds since the morphometric parameters correspond to this location. The distribution of flood records is well captured by the susceptibility index, while the observed flow types at the mouth show for only three of the five observations.

4 Discussion

4.1 Morphometric indicator

Figure 9 shows the boxplots of the composite morphometric indicator and the individual indicators for size, energy, hypsometry and shape. The indicators were grouped according to the classification of the watersheds carried out on the basis of the capacity to propagate debris flows to the fan of the watershed. The indicators calculated for La Negra creek watershed, La Chapa creek watershed and the subwatershed of Chiguaza creek (drainage area to the most downstream point affected by the debris flow on 19 May 1994) were plotted over the boxplots. La Chapa creek was classified as $H/L = 0.19$, and Negra creek and the subwatershed of Chiguaza creek as $H/L = 0.11$ according to the results of the MSF algorithm applied in these watersheds. The comparison of the composite morphometric indicator of the watersheds in the study area with that of the Chiguaza, La Chapa and La Negra watersheds, shows that the latter watersheds have a low indicator. This is mainly due to the size indicator, that in comparison with the size of the watersheds in the areas assigns low values, with the lowest being the indicator of La Negra creek which has an area of 68.4 km^2 (the largest area in the analysis). It is important to take into account that the composite morphometric indicator not only involves the capacity of the watershed to propagate debris flows but also the flashiness, this means that watersheds with the characteristics to propagate debris flows are not necessarily the flashiest. From the results of the size indicator shown in Fig. 9b, it can be observed that in general watersheds classified as 0.19D exhibit high values of the indicator. However, the size indicator does not discriminate between processes. This can be due to the scale of the analysis, since all the analyzed watersheds can be considered small. In the principal component analysis, the Size Indicator has the highest weight in the total morphometric indicator (see Eq. 7). Several studies have shown that drainage area is correlated with other morphometric parameters, for example, De Scally and Owens (2004) suggest that drainage area acts as a surrogate for the channel gradient and Gray (1961), and Shreve (1974) showed the correlation between length of the main stream and drainage area. Similar to the findings of other authors (Mesa, 1987; Gray, 1961; Shreve, 1974) a high determination coefficient was found between the logarithm of the stream length and the logarithm of drainage area ($R^2 = 0.92$). The same behaviour is exhibited by the logarithm of length of the watershed ($R^2 = 0.90$), logarithm of watershed width ($R^2 = 0.95$) and logarithm of perimeter of the watershed ($R^2 = 0.96$). The empirical relationship between length of the main stream (longest stream) and the area is known as Hack's law (Hack, 1957). The exponent of the power law may vary slightly from region to region, but it is generally accepted to be slightly below 0.6 (Rigon et al., 1996). In the study area this exponent corresponds to 0.59. Several authors have tried to explain the relationship between main stream length and basin area (Mantilla et al., 2000). The conclusion reached by Willemin (2000) indicates that there is some aspect of the evolution of fluvial systems not yet understood, that somehow takes into account three geometric components (basin elongation, basin convexity and stream sinuosity), none of which is particularly well correlated with basin area, and produces a robust relationship between main stream length and basin area. This conclusion is coherent with the findings of this study, where elongation does not show a strong correlation with basin area nor a trend to more elongated basins with increasing size of the watershed, as it is not in the same principal component (see Table 2). The energy indicator is composed of the relief ratio, the mean watershed slope, the stream slope, the Melton number and the mean of the multiresolution index (MRI). As suggested by Gallant (2003), the MRI can lead to identify similarities and differences between catchments which in this analysis correspond to the energy of the watersheds. High Melton numbers have been previously used as an effective discriminator of debris flow dominated watersheds. However, the threshold for the Melton number varies significantly depending on the region, ranging from 0.5 (Welsh and Davies, 2010) to 0.75 (De Scally and Owens, 2004). Despite the variability of its components, the energy indicator clearly distinguishes between 0.19D watersheds. Some superposition of values occurs but the interquartile range of 0.19D is separated from the interquartile ranges of the other two classifications (see Fig. 4). In terms of energy it is more difficult to distinguish between 0.11D watersheds and C watersheds. However, the mean and the first and third quartiles of the energy indicator for 0.11D is higher than in the case of C watersheds, but with a wider range of superposition. The high values of the energy indicator for the subwatershed of Chiguaza, La Chapa and La Negra creeks is consistent with the processes that take place in the watersheds.

Regarding the hypsometric indicator, since the hypsometric integral decreases as mass is removed from the watershed it follows that an inverse relationship between hypsometric skewness and the hypsometric integral exists (Harlin, 1984). This condition was found in the study area with a determination coefficient of 0.71. The same behaviour is exhibited by the density skewness ($R^2 = 0.82$) and hypsometric Kurtosis ($R^2 = 0.45$), where small values are characteristic of large integral values and small skewness. The density kurtosis shows no correlation with the hypsometric integral, this is reflected in the low correlation of this parameter with the corresponding principal component in the analysis (see Table 2). Headward erosion that starts at the lower reaches would represent a higher possibility of debris flow affecting the urbanized fans of the watersheds, therefore this increase in susceptibility would be represented by high hypsometric integrals, low hypsometric skewness and negative density skewness. Furthermore, according to Cohen et al. (2008) higher hypsometric integral values (greater than 0.5) represent catchments dominated by diffusive erosion processes (concave down hypsometric curve) while lower values (less than 0.5) represent fluvial dominated catchments (concave up hypsometric curve). Therefore the hypsometric integral is linked to erosion process, landform curvature and landscape morphology.

The boxplots of the hypsometric indicator (see Fig. 9b) do not show a differentiation between the classification of watersheds based on the capacity to propagate debris flows. The superposition of the values of the hypsometric indicator obtained for Chiguaza, La Chapa and Negra creeks shows interesting results, mainly for the case of La Chapa creek where the value classified as high in comparison with the other watersheds. Linking this result with the slope–area plot (Fig. 5) where no fluvial dominated area was identified for La Chapa creek, it can be inferred that there is a dominance of diffusive processes (characteristic of debris flows) in this watershed that is captured by the morphometric indicators. Therefore, the hypsometric indicator may contribute to explain the dominance of processes that supply sediment in the watershed. The availability of sediment is one of the determining factors for the occurrence of debris flows. However, its assessment requires extensive field work and detailed sediment source analysis. This assessment is not replaced by the hypsometric indicator, but for the scale of the analysis this indicator is considered to significantly contribute in the susceptibility recognition.

For the case of the shape indicator, drainage density was found to be correlated with the principal component related to the shape of the watersheds, which confirms its relation with the physiographic characteristics of the watersheds (Gregory and Walling, 1968). The boxplots of Fig. 9b shows that the capacity to transport debris flows is independent of the shape indicator. However, the values of the indicator for the three watersheds used as test areas (Chiguaza, La Chapa and Negra) are in the range of high values, particularly for Chiguaza and Negra creeks show a very high value. These two watersheds are very similar in terms of shape, hypsometry and energy.

4.2 Debris flow propagation

In the MSF algorithm two angles of reach were used $H/L = 0.11$ and $H/L = 0.19$ and a binary result was obtained for each watershed depending on whether the propagation area reaches the fan or not. However, independently of the classification of flow type of the watershed based on the type of flow at the mouth, other types of flow can occur in other areas of the watersheds, as is the case with the Chiguaza creek, where one of the most serious events recorded in the study area took place in 1994. On the 19 May 1994, a debris flow occurred in the upper basin affecting 830 people and causing the death of 4 people (JICA, 2006). The classification of the type of flows at the mouth of this watershed is clearwater flow. However in upper areas were the supply of sediment is high, the morphometric conditions favour debris flows and the landcover is characterised by areas with bare soil. Figure 10 shows a detail of Fig. 6b. The inset shows the extent of the debris flow using the MSF algorithm as well as the observed propagation area. The comparison of the observed runout distance of this event and the propagation areas shows a good agreement with the results of the MSF model, although deviations from the propagation areas exist in the final part of the runout (see inset). The deviations from the propagation area occur at bridges, which agrees with the analysis of the event carried out by JICA (2006) that concluded that obstructions in crossings had significantly influenced the trajectory of the flow. The bridges along the main stream of Chiguaza creek can be observed in Fig. 10. Simplified models like MSF cannot take the influence of bridges on the propagation of the flow into account. However, independently of the trajectory, the model seems to represent fairly well the downstream extent of the flow which is the main result needed for the analysis carried out in this study.

4.3 Land cover indicator, composite susceptibility index and comparison of results

Even if the morphometric indicator provides insight in the expected behaviour and dominant processes of the watersheds, it does not fully explain the distribution, characteristics and frequency of the flood events in the study area. This was considered to be due to the land cover effect on the hydrogeomorphic processes of the watersheds. Land cover can exert a positive influence in the case of vegetated surfaces, but also can enhance the susceptibility conditions when urban and bare soil areas are significant. It is important to consider that the mountains of Bogotá, mainly in the south of the city and in some localized areas of the east, have been subjected to illegal urbanization processes. The processes involved in informal settlement entail the construction of houses in the creeks, in some cases not only in the protection buffers but also in the channels. Furthermore, urbanization requires river crossings that in many cases are not technically designed and constitute dangerous obstructions to the flow as presented in Sect. 4.2. Another important aspect to consider is the accumulation of waste material in the channels, which during flood events is transported by the flow and obstructions are common in highly urbanized watersheds in the study area. The inclusion of the land cover influence in the analysis helps to explain the highly deteriorated conditions of some of the watersheds located in the south of the city where floods are frequent, but also to explain the lower occurrence of flood events in some watersheds in the east of the city where the presence of forests and protected areas has contributed to preserve the natural conditions of the watersheds. This suggests the importance of taking land cover into account when assessing the susceptibility to different types of flash floods in peri-urban areas of cities in mountainous areas.

5 Conclusions

A susceptibility indicator composed of a morphometric indicator and a land cover indicator was used to classify the flood threat of 106 watersheds located in the mountains in Bogotá (Colombia). Morphological variables recognized in literature to have a significant influence in flashiness and occurrence of debris flows were used to construct the morphometric indicator. Subsequently, this indicator was compared with the results of simplified debris flows propagation techniques to assess the capacity of the indicator in identifying the morphological conditions of a watershed that make it able to transport a debris flow. An important consideration during the analysis is that watersheds that are prone to debris flows are more dangerous than other flashy watersheds. The proposed susceptibility indicator, morphometric indicator and land cover indicator are intended to be easily derivable from digital elevation models and landuse images. The susceptibility index is useful in applications at regional scales for preliminary assessment and prioritization of detailed studies. These indicators do not intend to replace detailed approaches for hazard assessment of flash and debris flows, but to provide an initial guidance on where efforts should be concentrated in hazard investigation. A limitation of the method is that it does not take sediment availability into account which is a determining factor for debris flow occurrence and even if some morphometric indicators could be related to erosion and sediment availability, this factor should be assessed through other techniques. The morphological variables that were identified to enhance flood hazard, were analyzed through principal component analysis, finding that the 20 variables could be summarized in 4 components related to size, shape, hypsometry and energy of the watersheds. Size of the watersheds is the component that has the highest weight in the construction of the final morphometric indicator. This parameter has been repeatedly considered of high importance in the identification of hazard.

The lack of information in the records of past floods in the area prevents a systematic characterization of the type of floods that occur in each watershed of the study area.

Therefore, the parameters for three watersheds where the type of flood has been confirmed were used. One of the watersheds belongs to the study area while the other two are located in nearby regions of the Colombian Andes. The comparison of the indicators obtained for these watersheds were shown to be consistent with their behaviour.

The use of the slope–area curve to identify debris flows source areas showed an overestimation of potential sources when compared with other methods using empirical thresholds. However, it provides valuable information on the processes occurring in a watershed. The slope–area diagram obtained regionally can provide insight in the susceptibility at morphometric level when curves are compared between watersheds in different areas. In the case of the study area, the comparison of the slope–area curves of the Tunjuelo basin and the Eastern hills watersheds, allowed to conclude that the latter exhibit on average a higher slope for a given area, which is reflected in the energy indicator that is linked to the capacity to transport debris flows. The energy indicator was shown to distinguish watersheds with the capacity to transport debris flows to their fans. This indicator involves parameters previously successfully used to identify debris flow dominated watersheds. While the prevalence of debris flows in a watershed should be confirmed using detailed information on geology and geotecnics, this parameter can be taken as an initial assessment and for prioritization where to focus such detailed studies. The use of size, shape and hypsometry indicators in addition to the energy indicator, contribute to include valuable information in the analysis to integrally assess the watersheds. Size includes information regarding flashiness as well as shape. Hypsometry was found to be a promising indicator regarding the geomorphic evolution of the watershed and the erosion. Despite the ability of the morphometric indicator to identify the capability to transport debris flows, it was found not to be sufficient to explain the records of past floods in the study area. A land cover indicator was included, with the objective to involve in the analysis not only the benefit of vegetated areas but also the enhancement of hazard conditions produced by urbanization and soil deterioration. The indicator produced by the combination of the morphometric indicator and the land cover indicator improved the agreement between the results of the classification and the records of past floods in the area compared to when using only the morphometric indicator. This implies that even if morphometric parameters 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. The proposed susceptibility index can be used in a preliminary regional assessment to differentiate at spatial level the degree of flood susceptibility. This index is not absolute but relative to the study area. Its main purpose is to prioritize among the analyzed watersheds in order to carry out further studies at detailed scales allowing an estimation of the kind of flood hazard that can be expected in a watershed.

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References

Al-Rawas, G. and Valeo, C.: Relationship between wadi drainage characteristics and peak-flood flows in arid northern Oman, Hydrolog. Sci. J., 55, 377–393, 2010. 7582

Antonucci, A., Salvetti, A., and Zaffalon, M.: Credal networks for hazard assessment of debris flows, in: Advanced Methods for Decision Making and Risk Management in Sustainability, edited by: Kropp, J., and Scheffran, J., chap. 10, Nova Science, New York, 237–256, available at: http://www.idsia.ch/~alessandro/papers/antonucci2007d.pdf, 2007. 7557

Baker, V. R.: Hydrogeomorphic methods for the regional evaluation of flood hazards, Environ. Geol., 1, 261–281, 1976. 7582

Baumann, V. and Wick, E.: Debris flow susceptibility mapping at a regional scale along the National Road N7, Argentina, in: 2011 Pan-Am CGS Geotechnical Conference, available at: http://geoserver.ing.puc.cl/info/conferences/PanAm2011/panam2011/pdfs/GEO11Paper525.pdf, 2011. 7557, 7560

Bernal, G., Rosero, M., Cadena, M., Montealegre, J., and Sanabria, F.: Estudio de la Caracterización Climática de Bogotá y cuenca alta del Río Tunjuelo, Tech. rep., Instituto de Hidrología, Meteorología y Estudios Ambientales IDEAM – Fondo de Prevención y Atención de Emergencias FOPAE, Bogotá, 2007. 7553

Blahut, J., Horton, P., Sterlacchini, S., and Jaboyedoff, M.: Debris flow hazard modelling on medium scale: Valtellina di Tirano, Italy, Nat. Hazards Earth Syst. Sci., 10, 2379–2390, doi:10.5194/nhess-10-2379-2010, 2010. 7557

Bonnet-Staub, I.: Debris flow hazard assessment and mapping; application to a case study in the french Alps, in: International Conference on Geotechnical and Geological Engineering; GeoEng 2000, 25 pp., Technomic, 2000. 7557

Chaparro, O. I.: Evaluación de Riesgo por Flujos de Lodo en la Quebrada La Chapa, Municipios de Tasco and Socha (Boyacá), Ph. D. thesis, Universidad Nacional de Colombia, Bogotá, 2005. 7554

Chen, C.-Y. and Yu, F.-C.: Morphometric analysis of debris flows and their source areas using GIS, Geomorphology, 129, 387–397, 2011. 7551, 7556, 7582

Chen, T.-C., Wang, H.-Y., and Wang, S.-M.: Representative slope index of debris flow streams in Taiwan, in: Interpraevent 2010, 91–99, Taipei, 2010. 7582

Cohen, S., Willgoose, G., and Hancock, G.: A methodology for calculating the spatial distribution of the area-slope equation and the hypsometric integral within a catchment, J. Geophys. Res., 113, 1–13, 2008. 7570

Costa, J.: Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows, in: Flood Geomorphology, edited by: Baker, V. R., Kochel, R. C., and Patton, P. C., Wiley, New York, 113–122, 1988. 7554

Crosta, G. B. and Frattini, P.: Controls on modern alluvial fan processes in the central Alps, northern Italy, Earth Surf. Proc. Land., 29, 267–293, doi:10.1002/esp.1009, 2004. 7551, 7556, 7582

De Matauco, G. and Ibisate, A.: Análisis morfométrico de la cuenca y de la red de drenaje del río Zadorra y sus afluentes aplicado a la peligrosidad de crecidas, Boletín de la Asociación de Geógrafos, http://dialnet.unirioja.es/servlet/articulo?codigo=1079160, 2004. 7582

De Scally, F. and Owens, I.: Morphometric controls and geomorphic responses on fans in the Southern Alps, New Zealand, Earth Surf. Proc. Land., 29, 311–322, 2004. 7551, 7556, 7568, 7569, 7582

De Scally, F., Owens, I., and Louis, J.: Controls on fan depositional processes in the schist ranges of the Southern Alps, New Zealand, and implications for debris-flow hazard assessment, Geomorphology, 122, 99–116, 2010. 7551, 7556

DPAE: Diagnóstico Técnico 1836, Tech. rep., Direccion de Prevención y Atención de Emergencias de Bogotá, Bogotá, 2003a. 7553

DPAE: Diagnóstico Técnico 1891, Tech. rep., Direccion de Prevención y Atención de Emergencias de Bogotá, Bogotá, 2003b. 7553

DPAE: Dianóstico Técnico 1880, Tech. rep., Dirección de Prevención y Atención de Emergencias de Bogotá, Bogotá, 2003c. 7553

Gallant, J. C.: A multiresolution index of valley bottom flatness for mapping depositional areas, Water Resour. Res., 39, 1347–1360, 2003. 7556, 7557, 7569, 7582

Gray, D. M.: Interrelationships of Watershed Characteristics, J. Geophys. Res., 66, 1215–1223, 1961. 7568, 7582

Gregory, K. and Walling, D.: The variation of drainage density within a catchment, Hydrolog. Sci. J., 13, 61–68, 1968. 7570

Griffiths, P. G., Webb, R. H., and Melis, T. S.: Frequency and initiation of debris flows in Grand Canyon, Arizona, J. Geophys. Res., 109, F04002, doi:10.1029/2003JF000077, 2004. 7551, 7556

Hack, J.: Studies of longitudinal stream profiles in Virginia and Maryland, US Geol. Survey Prof. Paper, available at: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Studies+of+Longitudinal+Stream+Profiles+in+Virginia+and+Maryland, 1957. 7568

Hancock, G. R.: The use of digital elevation models in the identification and characterization of catchments over different grid scales, Hydrol. Process., 19, 1727–1749, doi:10.1002/hyp.5632, 2005. 7558

Harlin, J.: Statistical moments of the hypsometric curve and its density function, Math. Geol., 10, 59–72, doi:10.1007/BF01033300, 1978. 7557, 7582

Harlin, J.: Watershed morphometry and time to hydrograph peak, J. Hydrol., 67, 141–154, 1984. 7569, 7582

Hengl, T. and Reuter, H.: Geomorphometry: Concepts, Software, Applications, Elsevier, 1st Edn., 2009. 7560

Hollis, G. E.: The effect of urbanization on floods of different recurrence interval, Water Resour. Res., 11, 431, 1975. 7562

Horton, P. and Jaboyedoff, M.: Debris flow susceptibility mapping at a regional scale, 4th Canadian Conference on Geohazards, http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Debris+flow+susceptibility+mapping+at+a+regional+scale#1, 2008. 7557, 7558, 7559, 7560, 7565

Huang, X. and Niemann, J. D.: How do streamflow generation mechanisms affect watershed hypsometry?, Earth Surf. Proc. Land., 33, 751–772, doi:10.1002/esp.1573, 2008. 7556

Huggel, C., and Kääb, A.: Regional-scale GIS-models for assessment of hazards from glacier lake outbursts: evaluation and application in the Swiss Alps, Nat. Hazards, 3, 647–662, 2003. 7560, 7561

Hurtrez, J., Sol, C., and Lucazeau, F.: Effect of drainage area on hypsometry from an analysis of small scale drainage basins in the Siwalik Hills (Central Nepal), Earth Surf. Proc. Land., 808, 799–808, 1999. 7582

Jakob, M.: Morphometric and geotechnical controls of debris flow frequency and magnitude in southwestern British Columbia, Ph. D. thesis, University of British Columbia, available at: https://circle.ubc.ca/handle/2429/6147, 1996. 7562

Jakob, M. and Weatherly, H.: Debris flow hazard and risk assessment, Jones Creek, Washington, in: Landslide Risk Management, Proceedings, edited by: Hungr, Fell, Couture, and Eberhardl, Taylor & Francis, 533–541, 2005. 7550

JICA: Study on monitoring and early warning systems for landslide and floods in Bogotá and Soacha, Tech. rep., Japanese Internation Cooperation Agency – JICA, Bogotá, 2006. 7571

Kappes, M. S., Malet, J.-P., Remaître, A., Horton, P., Jaboyedoff, M., and Bell, R.: Assessment of debris-flow susceptibility at medium-scale in the Barcelonnette Basin, France, Nat. Hazards Earth Syst. Sci., 11, 627–641, doi:10.5194/nhess-11-627-2011, 2011. 7555, 7558, 7561

Koscielny, M.: Debris flow hazards due to land use change above source areas in torrent catchments. The case study of Les Arcs (Savoie, France), Debris flow 2008 2nd, 124, 161–170, available at: http://library.witpress.com/viewpaper.asp?pcode=RM09-015-1http://hal.archives-ouvertes.fr/hal-00584934/, 2008. 7561, 7562

Kostaschuk, R.: Depositional process and alluvial fan drainage basin morphometric relationships near banff, Alberta, Canada, Surf. Process. Land., 11, 471–484, 1986. 7551, 7556

Luo, W. and Harlin, J. M.: A theoretical travel time based on watershed hypsometry, JAWRA J. Am. Water Resour. As., 39, 785–792, doi:10.1111/j.1752-1688.2003.tb04405.x, 2003. 7556, 7582

Mantilla, R., Mesa, O., and Poveda, G.: Sobre la existencia de la ley de Hack en las cuencas hidrográficas de Colombia, in: XIV Seminario Nacional de Hidráulica e hidrología, available at: http://www.bdigital.unal.edu.co/4421/1/AA3319.pdf, 2000. 7568

Mesa, O. J.: On the Main Channel Length-Area Relationship for Channel Networks, Water Resour., 23, 2119–2122, 1987. 7568

Montgomery, D. R. and Foufoula-Georgiou, E.: Channel network source representation using digital elevation models, Water Resour. Res., 29, 3925–3934, doi:10.1029/93WR02463, 1993. 7558, 7559, 7565

Osorio, J. A.: El Río Tunjuelo en la Historia de Bogotá, 1900–1990, Alcaldia Mayor de Bogotá, Bogotá, primera ed edn., 2007. 7553

O'Brien, J. S.: Simulating mud flows guidelines, Tech. rep., 2006. 7553, 7554

Patton, P.: Drainage basin morphometry and floods, in: Flood Geomorphology, edited by: Baker, V. R., Kochel, R. C., and Patton, P. C., chap. 3, 51–64, Wiley, New York, 1988. 7556

Patton, P. and Baker, V.: Morphometry and floods in small drainage basins subject to diverse hydrogeomorphic controls, Water Resour. Res., 12, 941–952, doi:10.1029/WR012i005p00941, 1976. 7551, 7556, 7582

Pérez-Peña, J. V., Azañón, J. M., and Azor, A.: CalHypso: An ArcGIS extension to calculate hypsometric curves and their statistical moments, applications to drainage basin analysis in SE Spain, Comput. Geosci., 35, 1214–1223, 2009. 7557, 7582

Prochaska, A., Santi, P., Higgins, J., and Cannon, S.: Debris-flow runout predictions based on the average channel slope (ACS), Eng. Geol., 98, 29–40, 2008. 7561

Rengifo, O.: Modelaje de flujos de detritos potenciales a partir de un modelo de elevación digital SRMT (Shuttle Radar Topography Mission): cuenca alta del río Chama, noroeste de Venezuela, Revista Geográfica Venezolana, 53, 93–108, 2012. 7557

Rickenmann, D.: Empirical relationships for debris flows, Nat. Hazards, 19, 47–77, 1999. 7561

Rickenmann, D. and Zimmermann, M.: The 1987 debris flows in Switzerland: documentation and analysis, Geomorphology, 8, 175–189, 1993. 7555, 7559, 7560, 7561

Rigon, R., Rodriguez-Iturbe, I., and Maritan, A.: On Hack's law, Water Resour., 32, 3367–3374, 1996. 7568

Rowbotham, D., De Scally, F., and Louis, J.: The identification of debris torrent basins using morphometric measures derived within a GIS, Geogr. Ann., 87, 527–537, 2005. 7551, 7556, 7582

Saczuk, E. A. R.: GIS-Based Modeling of Debris Hows in Banff National Park, Alberta, Ph. D. thesis, University of Manitoba, Winnigpegm Manitoba, 1998. 7582

Sakals, M. and Innes, J.: The role of forests in reducing hydrogeomorphic hazards, For. Snow Landsc. Res., 80, 11–12, http://andrewsforest.oregonstate.edu/pubs/pdf/pub4010.pdf, 2006. 7562

Sanchez-Marre, M., Comas, J., and Rizzoli, A.: Spatially distributed identification of debris flow source areas by credal networks, in: iEMS, 8 pp., available at: http://www.iemss.org/iemss2008/uploads/Main/S04-16-Salvetti_et_al-IEMSS2008.pdf, 2008. 7556, 7557

Santangelo, N., Daunis-i Estadella, J., Di Crescenzo, G., Di Donato, V., Faillace, P. I., Martín-Fernández, J. a., Romano, P., Santo, A., and Scorpio, V.: Topographic predictors of susceptibility to alluvial fan flooding, Southern Apennines, Earth Surf. Proc. Land., 37, 803–817, 2012. 7551, 7554, 7555, 7556

Santos, R.: Topographic signature of debris flow dominated channels: implications for hazard assessment, in: Monitoring, Simulation, Prevention and Remediation of Dense and Debris Flows, edited by: Lorenzini, G. and Emmanouloudis D. B. C. A., WIT Press, Southampton, 301–310, 2006. 7557, 7558, 7559, 7565

Schueler, T.: Site planning for urban stream protection, Metropolitan Washington Council of Governments, available at: http://www.ci.milpitas.ca.gov/_pdfs/cwp_site_planning/ch4.pdf, 1995. 7562

Seidl, M. and Dietrich, W.: The problem of channel erosion into bedrock, Catena supplement, 101–124, available at: http://geography.uoregon.edu/amarcus/geog607w09/Readings/Seidl-Dietrich1992_Catena_Bedrock.pdf, 1993. 7558, 7559, 7565

Shreve, R. L.: Variation of mainstream length with basin area in river networks, Water Resour. Res., 10, 1167–1177, 1974. 7568, 7582

Sodnik, J. and Miko, M.: Estimation of magnitudes of debris flows in selected torrential watersheds in Slovenia, Acta geographica Slovenica, 46, 93–123, 2006. 7582

Stock, J. and Dietrich, W. E.: Valley incision by debris flows: evidence of a topographic signature, Water Resour. Res., 39, 1089, doi:10.1029/2001WR001057, 2003. 7558, 7559

Takahashi, T.: Estimation of potential debris flows and their hazardous zones: soft countermeasures for a disaster, Nat. Disast. Sci., 3, 57–89, 1981. 7555

Tucker, G. and Bras, R.: Hillslope processes, drainage density, and landscape morphology, Water Resour. Res., 34, 2751–2764, 1998. 7558

UNAL and INGEOMINAS: Generación de una guía metodológica para la evaluación de la amenaza por movimientos en masa tipo flujo, caso piloto Cuenca Quebrada La Negra, Tech. rep., INGEOMINAS, Bogotá, 2007. 7553

Wan, S., Lei, T., Huang, P., and Chou, T.: The knowledge rules of debris flow event: a case study for investigation Chen Yu Lan River, Taiwan, Eng. Geol., 98, 102–114, 2008. 7582

Weissmann, G. S., Bennett, G. L., and Lansdale, A. L.: Factors controlling sequence development on Quaternary fluvial fans, San Joaquin Basin, California, USA, Geological Society, London, Special Publications, 251, 169–186, available at: http://sp.lyellcollection.org/cgi/doi/10.1144/GSL.SP.2005.251.01.12, 2005. 7582

Welsh, A. and Davies, T.: Identification of alluvial fans susceptible to debris-flow hazards, Landslides, 8, 183–194, 2010. 7582

Welsh, A. J.: Delineating debris-flow hazards on alluvial fans in the Coromandel and Kaimai regions, New Zealand, using GIS, Ph. D. thesis, University of Canterbury, Canterbury, 2007. 7550, 7551, 7554, 7555, 7582

Wilford, D. J., Sakals, M. E., Innes, J. L., Sidle, R. C., and Bergerud, W. A.: Recognition of debris flow, debris flood and flood hazard through watershed morphometrics, Landslides, 1, 61–66, 2004. 7550, 7551, 7553, 7554, 7555, 7556, 7582

Willemin, J. H.: Hack ’ s law: sinuosity, convexity, elongation, Water Resour., 36, 3365–3374, 2000. 7568

Willgoose, G. and Hancock, G.: Revisiting the hypsometric curve as an indicator of form and process in transport-limited catchment, Earth Surf. Proc. Land., 23, 611–623, doi:10.1002/(SICI)1096-9837(199807)23:7<611::AI%D-ESP872>3.0.CO;2-Y, 1998. 7556, 7582

Zavoianu, I.: Morphometry of drainage basins/Ion Zavoianu;[translated from the Romanian by Adriana Ionescu-Parau], Elsevier; Editura Academiei Republicii Socialiste Romania, Amsterdam, available at: http://nla.gov.au/nla.cat-vn4083687, 1985. 7582

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Table 1. Morphometric variables used in the analysis. Note that L corresponds to the length of the streams in a watershed, $H_{\max}$ and $H_{\min}$ correspond to the highest and lowest elevation in a watershed respectively.

Variable	Relevance	Reference
Area (A)	Correlated with discharge; proportional to sediment storage in the catchment; wide basins collect a large amount of water, which can dilute the flood reducing the probability of debris flow forming in a first-order basin reaching the alluvial fan. Correlated with other morphometric parameters.	Crosta and Frattini (2004); Baker (1976); De Scally and Owens (2004); Gray (1961); Shreve (1974)
Perimeter (P)	Base for several watershed shape indices.	Zavoianu (1985)
Drainage density $\mathrm{DrD} = \sum_{i=1}^{n} L_i/A$	Correlated with base flow, peak flood discharge and flood potential.	Baker (1976); Patton and Baker (1976)
Watershed length (L_{wshd})	Has been used to differentiate between watersheds prone to debris flows and debris floods in combination with the Melton ratio.	Wilford et al. (2004)
Watershed mean slope (S)	Related to flashiness of the watershed. Used to discriminate between debris flow and clearwater flood domiunated watersheds.	Al-Rawas and Valeo (2010); De Matauco and Ibisate (2004)
Main stream slope (StrS)	Used to discriminate between processes in watersheds.	Welsh (2007)
Relief ratio $R_{\mathrm{Ra}} = (H_{\max} - H_{\min})/L_{\mathrm{wshd}}$	Used to describe debris flow travel distance and event magnitude.	Chen and Yu (2011)
Shape factor $\mathrm{SF} = A/L_{\mathrm{wshd}}$	Related to flow peak and debris flow occurrence.	Chen and Yu (2011); Al-Rawas and Valeo (2010); Wan et al. (2008)
Main stream length (L_{str})	Used to discriminate between processes in watersheds.	Chen et al. (2010)
Circularity coefficient $C = 4\pi * A/P^2$	The more circular a watershed is, the sharper its hydrograph, this means the flashiness increases and therefore the threat of flooding is higher.	De Matauco and Ibisate (2004)
Elongation ratio $E = 2/(L_{\mathrm{wshd}}(A/\pi)^{0.5})$	floods travel less rapidly; have less erosion and transport potential; and less suspended load in elongated watersheds. An elongated shape favors a diminution of floods because tributaries flow into the main stream at greater intervals of time and space.	Zavoianu (1985)
Watershed width $W_{\mathrm{wshd}} = A/L_{\mathrm{wshd}}$	Related to the size of fans.	Weissmann et al. (2005)
Length to width ratio (LW)	Measure of elongation.	Zavoianu (1985)
Melton ratio $M = (H_{\max} - H_{\min})/A^{0.5}$	Frequently used to discriminate among hydrogeomorphologic processes.	Welsh and Davies (2010); Sodnik and Miko (2006); Saczuk (1998); Rowbotham et al. (2005); Wilford et al. (2004)
Hypsometric integral (HI)	Linked to the stage of geomorphic development of the basin; indicator of the erosional stage; related to several geometric and hydrological properties such as flood plain area and potential surface storage; the hypsometric curve has been used to establish empirical correlations between the hypsometric parameters of a watershed and its observed time to peak. Used to differentiate between processes in the watershed.	Pérez-Peña et al. (2009); Harlin (1978); Luo and Harlin (2003); Willgoose and Hancock (1998); Hurtrez et al. (1999)
Hypsometric skewness (Hs)	Reflects the amount of headward erosion attained by streams; high values are characteristic of headward development of the main stream and its tributaries, representing the amount of headward erosion in the upper reach of a basin.	Harlin (1984)
Hypsometric kurtosis (Hk)	Large values signify erosion in both upper and lower reaches of a basin.	Harlin (1978)
Density skewness (DHs)	Indicates where slope changes are concentrated, and if accelerated forms of erosion, like mass wasting, are more probable in the basin's upper reaches. When density skewness equals 0 equal amount of change is occurring, or has occurred, in the upper and lower reaches of the watershed.	Harlin (1984)
Density kurtosis (DHk)	Relates to the mid-basin slope.	Harlin (1984)
Average of the multiresolution index – MRI Mean (MRIm)	Discriminates between depositional regions and erosional regions.	Gallant (2003)

Table 2. Principal components and corresponding variables. The symbol column shows the abbreviation used in the formulas and loading corresponds to the correlation of each variable with the corresponding principal component. Variables belonging to the PC1 were log transformed and variables with the symbol * were transformed as 1 – (value – minimum input value)/(maximum input value – minimum input value).

Variable	Symbol	Loading
PC1 – Size – % of Variability Explained = 30 %		
(log)Perimeter*	P	0.96
(log)Length of the watershed*	L_{wshd}	0.97
(log)Length of the main stream*	L_{Str}	0.95
(log)Area*	A	0.92
(log)Watershed Width*	W_{wshd}	0.83
PC2 – Shape – % of Variability Explained = 28 %		
Elongation ratio	E	0.93
Watershed legth to width*	LW	0.93
Circularity coeffiecient	C	0.95
Shape factor	SF	0.90
Drainage density*	DrD	0.66
PC3 – hypsometry – % of Variability Explained = 22 %		
Hypsometric skewness*	Hs	0.98
Hypsometric integral	Hi	0.90
Density skewness*	DHs	0.88
Hypsometric kurtosis*	Hk	0.91
Density kurtosis*	DHk	0.37
PC4 – Energy – % of Variability Explained = 20 %		
Relief ratio	R_{ra}	0.85
Watershed slope	S	0.89
Stream slope	StrS	0.63
Melton number	M	0.72
MRI mean*	MRIm	0.90

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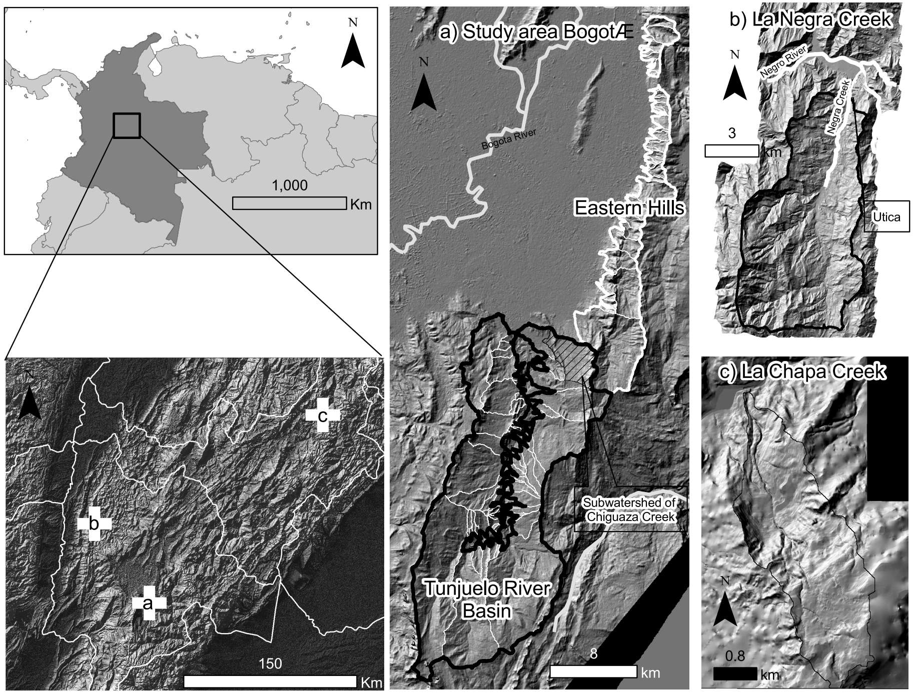

Fig. 1. Location of the study areas.

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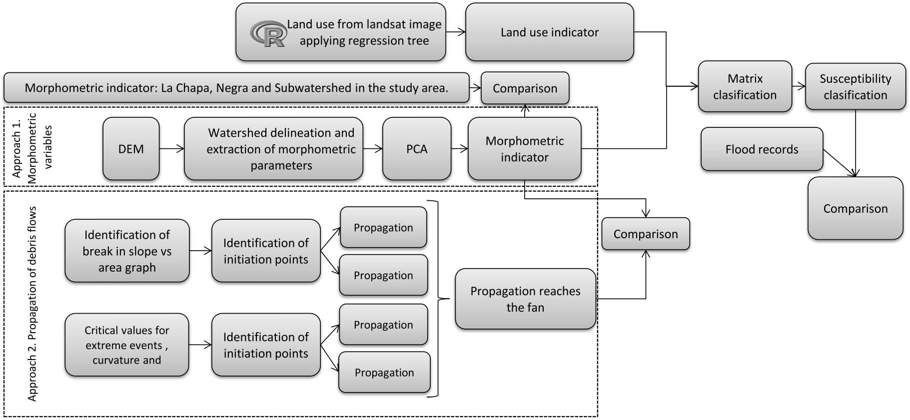

Fig. 2. Schematic representation of the methodology.

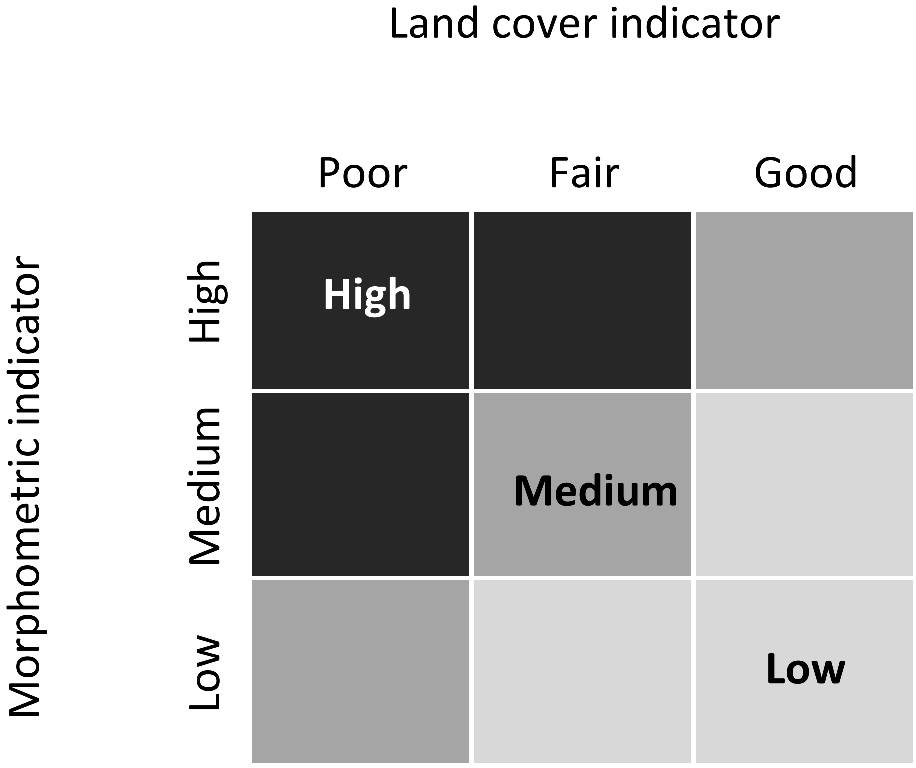

Fig. 3. Matrix of classification of susceptibility.

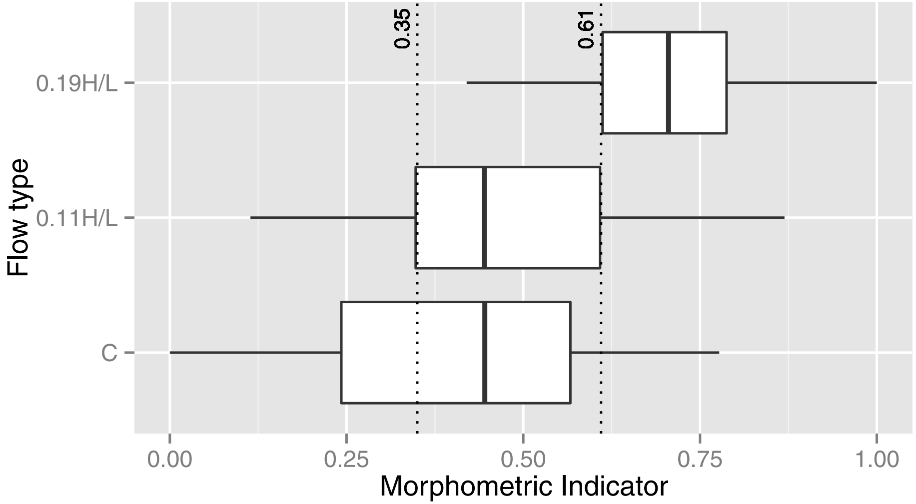

Fig. 4. Morphometric indicator with values rescaled from 0 to 1.

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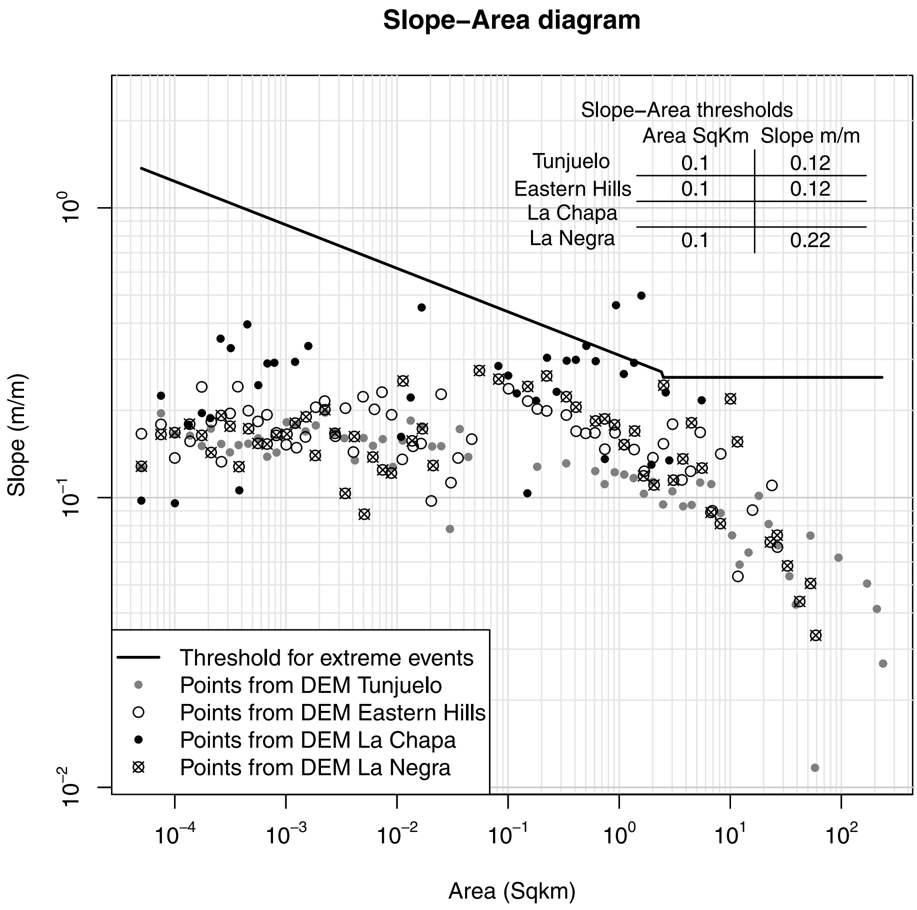

Fig. 5. Slope–area diagram for the study area and comparative areas.

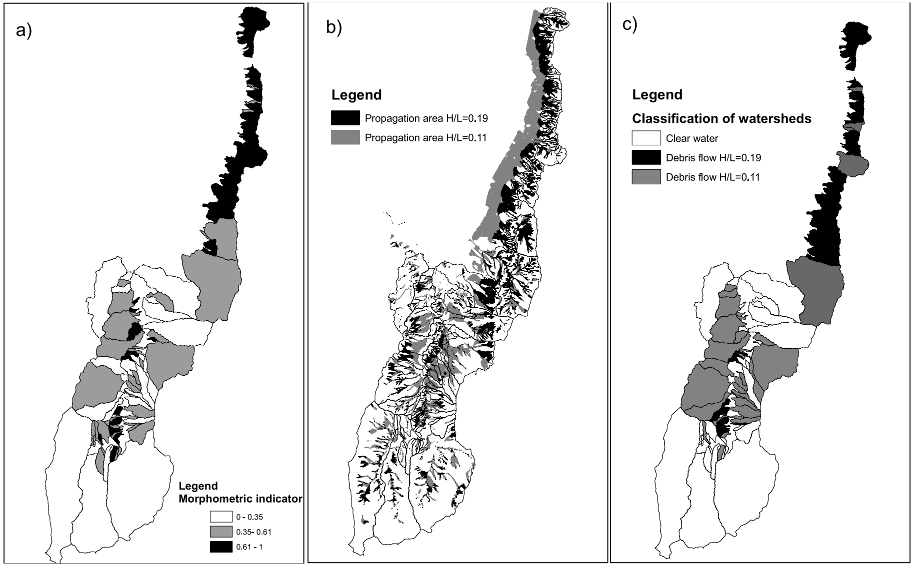

Fig. 6. **(a)** morhometric indicator, **(b)** propagation of debris flows, **(c)** classification of watersheds.

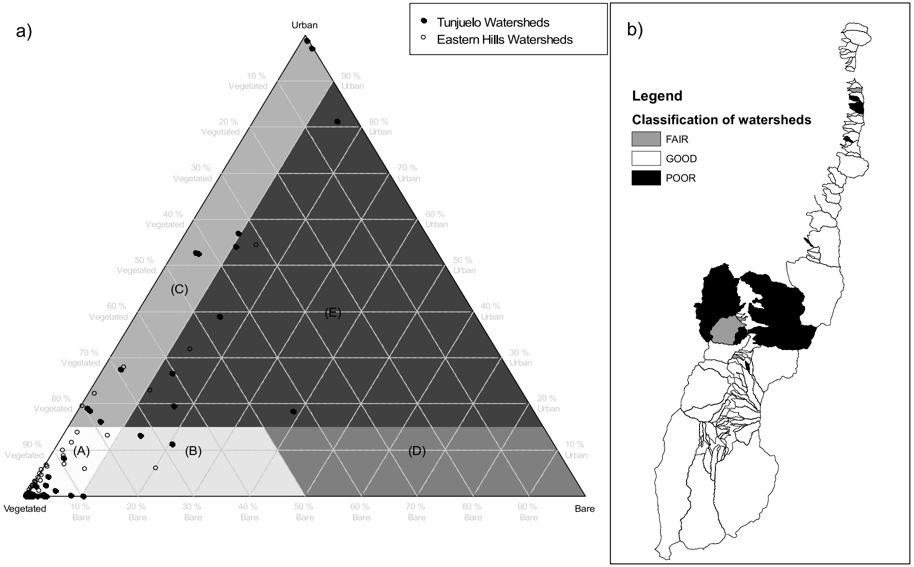

Fig. 7. (a) ternary plot for classification of watersheds according to landcover. The description of the zones of the plot is as follows: (A) low percentage bare soil, low percentage of urban soil and high percentage of vegetated areas; (B) high percentage of bare soil, low percentage of urban soil and high percentage of vegetated areas; (C) low percentage of bare soil, high percentage of urban land and low percentage of vegetated areas; (D) high percentage of bare soil, low percentage or urban soil and low percentage of vegetated land; (D) high percentage of bare soil, high percentage of urban area and low percentage of vegetated cover. **(b)** classification of watersheds according to landcover.

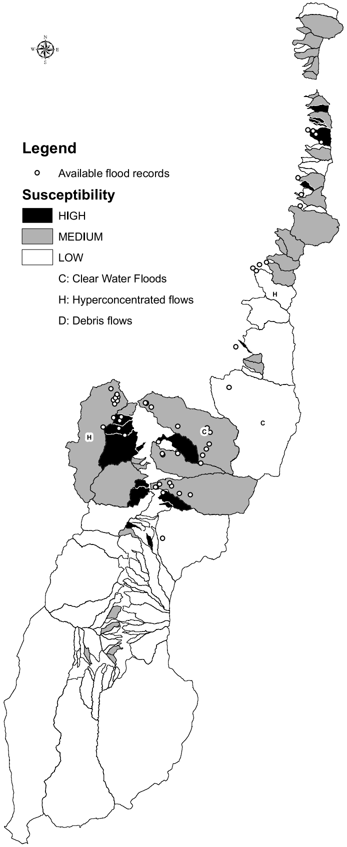

Fig. 8. Susceptibility classification.

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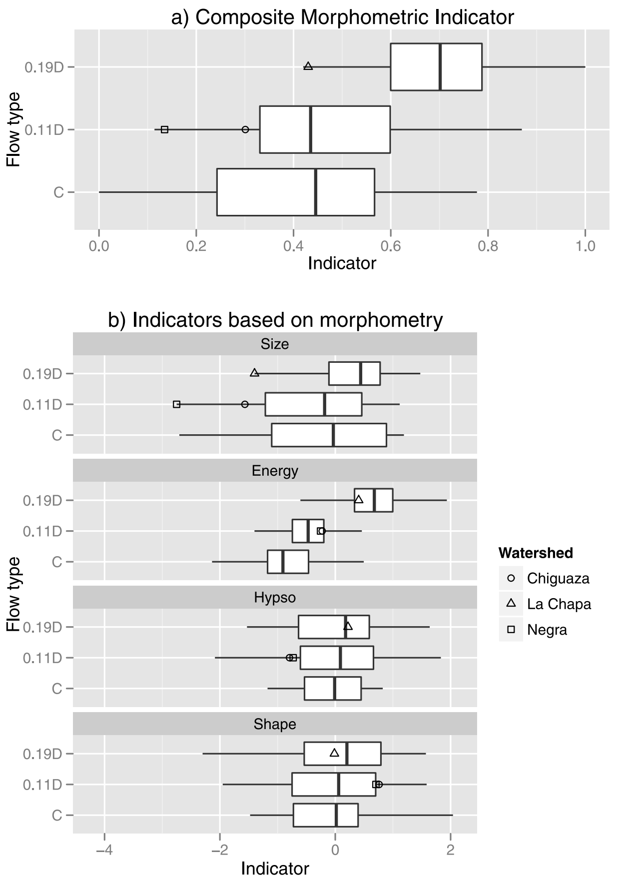

Fig. 9. (a) composite morphometric indicator, **(b)** indicators based on morphometry. NOTE: 0.19D and 0.11D correspond to watersheds that can propagate debris flows to their fans considering reach angles of 0.19 and 0.11 respectively.

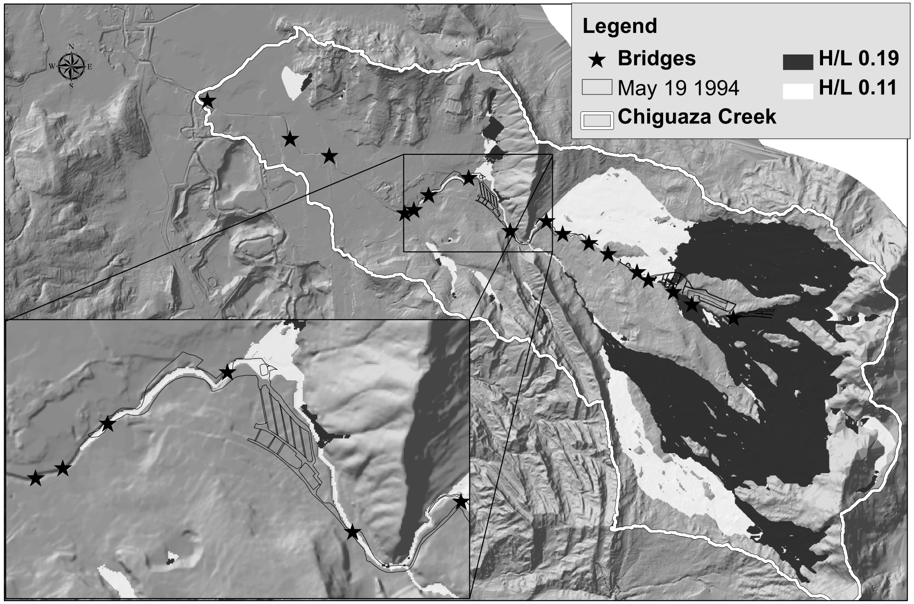

Fig. 10. Affected area in the Chiguaza creek on 19 May 1994 compared with propagation areas obtained from the MSF model.