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Natural Hazards and Earth System Sciences
Discussions

Interactive comment on "Regional flood susceptibility analysis in mountainous areas through the use of morphometric and land cover indicators" *by* M. C. Rogelis and M. Werner

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We thank Dr. Pöppl for an extensive and careful review of our manuscript. The comments and suggestions have helped to improve the manuscript. For ease of reading we have copied the reviewer comments, as well as our response.

GENERAL COMMENTS

The paper presents a new methodology (index) for analyzing regional "flash flood" susceptibility. The index considers morphometric and land cover parameters to discriminate between debris flow and clear water flow dominated watersheds in order "to understand the level of threat that floods in the watersheds pose". The presented approach intends to overcome limitations in the availability of field-derived data by combining morphometric and land cover characteristics derived from digital elevation models and satellite imagery. The approach is new, innovative and promising, but suffers from sufficient validation of the modelling results. Moreover, some further issues regarding approach and style call for a major revision of the manuscript (see below).

RESPONSE:

As with the comment of reviewers 1 and 2 we agree that the validation of the proposed method is of key importance. Since this is a key comment raised by all three reviewers, we present a common response as follows:

The absence of field evidence on past occurrence of debris flows that can support validation of the proposed method is an obstacle to the full validation of the proposed methodology. This is in fact the key comment raised by all three reviewers. However, such field evidence is particularly difficult to obtain. This is indeed so in the peri-urban areas of Bogota as the urbanization processes have significantly altered the catchments. Furthermore, the susceptibility of the watersheds may not be independent of the land use in the watersheds, which could undermine possible validation using field evidence if that were to exist. In fact it is this dilemma that is the main motivation for the development of the research. The method proposed is primarily aimed at establishing an index that can help prioritise watersheds at the regional scale. These can then be subjected to a more detailed field investigation and possible modelling, given that such a detailed analysis of all watersheds is not practicable.

Apart from the limited amount of flood records in the study area, three additional watersheds were used, two of which are located outside of the study area. This was clarified in the paper. Despite these three additional watersheds we do agree that the number of watersheds is still limited. The lack of flood records is a common condition in developing cities. In this revision we have extended the classification of the watersheds based on the database of floods in the area (maintained by the emergency response authority), and have made a more exhaustive analysis of field reports on past flood events. Based on these reports we have been able to increase the number of watersheds classified on the historical events to 11. Additionally, the results of the indicator proposed were compared with an independent method based on the propagation of debris flows using a digital elevation model.

In order to give more clarity about the method used for comparing the morphometric indicator with the results of the independent method and the available information, the methodology section was modified. Section 2.2 explains the approach that was followed, explaining the motivation and procedure used to develop the morphometric indicator, its comparison with the results of the debris flow propagation model, the flow type classification of the 11 watersheds and the comparison with the results from the three additional watersheds. In the subsections of the Methodology section a detailed and clearer explanation of the use of these data was included. Regarding the comparison methodology, this was improved using contingency tables providing a quantitative support to the discussion and conclusions.

Additionally, we think that one of the main issues underlying the concern raised by the referees is that the scope of the paper is perhaps not as clear as it could be. Regarding the lack of documents describing the occurrence and characteristics of floods a clarification on the scope of the paper was added to the introduction:

"When historical data on the occurrence of flash floods and debris flows are not available, the recognition of hydro-geomorphological hazards can be carried out through field work analysis applying methods such as the proposed by (Aulitzky, 1982) based on hazard indicators, or through stratigraphic evidence in conjunction with age control (Jakob et al,2005; Giraud,2005). However, such fieldwork and detailed geological and geotechnical analysis at the regional scale requires significant resources and time,

and may not be practicable in the extensive peri-urban areas of cities in mountainous areas such as those in the Andean cordillera. Furthermore, urbanisation processes in the peri-urban areas of these cities make geologic investigation difficult. Moreover the history of the watershed may not be a conclusive indicator of current hazard conditions, since anthropogenic intervention can play a significant role in the hazard dynamics. This calls for a more rapid yet reliable assessment of the watersheds, allowing a prioritization of watersheds where a more detailed analysis based on field data is to be carried out."

SPECIFIC COMMENTS

1. **The title is misleading. As the main focus is on debris flows and not on floods, the title should be changed accordingly. (major issue)**
   RESPONSE:
   The title was changed to “Regional flash flood susceptibility analysis in mountainous peri-urban areas through morphometric and land use indicators”.

2. **Abstract (lines 20-21): What are “good morphometric conditions”? Please avoid such terms. (minor issue)**

   RESPONSE: The word “good” changed to "favourable"

3. **Introduction (p. 7551, line 3): What are “clear water fans”? Do you mean “alluvial fans”? (minor issue)**
   RESPONSE: The term “clear water fans” changed to alluvial fan

4. **Study area. Are all of the studied catchments comparable in terms of lithology (you did not mention the lithology of the catchments!)? What about river engineering? Are there any protection measures (e.g. dams) installed in the systems that potentially influence channel processes? (major issue)**
   RESPONSE:

Lithology:
The following was added to the study area description:
"The area is mainly formed by sandstones of Cretaceous and Palaeogene age. This sedimentary rock forms surrounding mountains up to 4000 m altitude, thus reaching to some 1500 m above the level of the high plain of Bogotá (Torres et al, 2005)."
River engineering:
The following information was included:
"The reaches of the creeks in the urban areas have been subjected to significant intervention and occupation. Most of the creeks in the Eastern Hills discharge into the storm water system though structures with a low hydraulic capacity (less than a return period of 10 years) (Hidrotec, 1999). The streams that discharge into the Tunjuelo river have been severely modified mainly in the reaches near the confluence, albeit without a comprehensive flood management plan. Flood control structures in the study area have been constructed in the main stream of the Tunjuelo river, including a dry dam in the middle basin, three retention basins in the lower basin and levees. Additionally, there are two reservoirs in the upper basin of the Tunjuelo River that supply water to Bogotá. Conversely, flood control works have not been constructed in any of the watersheds in the study area except for the Chiguaza watershed, where flood control works were constructed near the confluence with the Tunjuelo river in 2008."

5. **Study area (p. 7553, line 2). Annual precipitation varies [: : :] in a bimodal regime". Please give information on the timing of the rainy seasons (Feb-May, Oct-Nov?). (minor issue)**
RESPONSE: The paragraph was improved as follows:

"The mean annual precipitation varies from 600 mm to 1200 mm in a bimodal regime with rainy seasons in April-May and October-November (Bernal, 2007)."

6. **Methodology. Section 2.2. You present the variety of definitions for the different processes, but you don't state to which you (!) refer to. (minor issue)**
RESPONSE:
A clarification was added in the introduction:
"This paper proposes a method for regional assessment of flash flood susceptibility under limited availability of data in urban environments, where flash floods occur as debris flows, hyperconcentrated flows or clear water flows as defined by Costa (1988)."

7. **Methodology. Section 2.2.1 (p. 7555, lines 19-20). Please explain the DEM construction in more detail (base map?, year?; procedure). (minor issue)**
RESPONSE:
A clarification was added:

"The main input for both approaches is a five meter resolution raster DEM. This was constructed using contours that are available in the peri-urban area at intervals of 1 meter. The contours were processed to obtain a triangulated irregular network, which was subsequently transformed into the 5m resolution raster through linear interpolation."

8. **Methodology. Section 2.2.1 (p. 7555, lines 21-22). Please explain more detailed how the parameter extraction was done, esp. for which units (whole catchment, subcatchments, river reaches/distances etc.?)! (major issue)**
RESPONSE:
A clarification was added in the Methodology:

"The units of analysis correspond to the watersheds delineated up to the discharge of the water body into the Tunjuelo River in the case of the streams

located in the Tunjuelo river basin, and to the discharge into the storm water system in the case of the streams located in the Eastern Hills."
A clarification was added in section 2.2.1:

"The morphometric parameters shown in Table 1 were extracted for each watershed from the digital elevation model of the study area using GIS tools."

9. **Methodology. Section 2.2.1 (p. 7559, lines 17-18). You mentioned that the break in the slope-area diagram was inferred visually. Please shortly state the chosen criteria for threshold determination. (minor issue)**
RESPONSE:

To avoid subjectivity in the procedure, the visual determination of the breaks in the slope-area diagram was eliminated and replaced by the use of segmented regression. The explanation was added to subsection Propagation of debris flows as follows:

"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 obtained using segmented regression, in order to determine a threshold to differentiate two regions, one dominated by erosive processes and the other dominated by fluvial erosive processes. This threshold will be used as the topographic signature of debris flow."

10. **Methodology. Section 2.2.1 (p. 7560, line 7). What do you mean by "extreme events"? Please define (better). (minor issue)**
RESPONSE:
A clarification was added in the section Propagation of debris flows:

"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 to identify debris flow source areas, is based on the relationship between slope and drainage area shown in Equation 1 and Equation 2 which were built on observations made by Rickenmann and Zimmermann (1993). Horton and Jaboyedoff (2008) denominated this criteria as threshold for extreme events given that the 1987 events on which the threshold is based, were considered as extraordinary and this denomination allowed differentiation from other set of points used by Horton and Jaboyedoff (2008)."

11. **Methodology. Section 2.2.1 (p. 7560, line 26). Please explain shortly the variables of the H/L ratios (give the equation?). (minor issue)**
RESPONSE:
In the subsection Propagation of debris flows the following explanation was included:

"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 H and length from the debris flow initiation point to the downstream extent of the debris flow runout L) (Horton and Jaboyedoff, 2008; Kappes et al., 2011)."
Additionally, when the angle of reach is mentioned in the text the words "(H/L ratio)" are used for clarity.

12. **Methodology. Section 2.2.2 (p. 7561, paragraph 1). Please explain how you performed the land cover classification (visual delineation?, classification based on spectral reflectance (bands)?). (major issue)**
RSPONSE:

A clarification was added:

"The land cover indicator was constructed by analysing the characteristic land cover of each watershed, which was obtained from the classification of a LANDSAT TM5 image taken in 2001. The LANDSAT image was classified using a supervised classification algorithm. The reflectance values for different spectral wavelengths were extracted from the LANDSAT image for training samples with known land cover obtained from the inspection of a high-resolution Google image. The reflectance data of the training samples were used in a recursive partitioning algorithm from which a classification tree is obtained and applied to all pixels of the LANDSAT multiband image to establish separability of the classes based on the spectral signatures."

13. **Methodology. Section 2.2.3. You weighted both indicators equally. Why? This would mean that land use and morphology have the same impact on the occurrence of debris flows, which might or might not be true (see literature!!). This is (just) an assumption of yours! Justify your assumption. (major issue)**
RESPONSE:

In order to avoid subjectivity in the definition of the structure of the matrix to combine the morphometric indicator and the land cover indicator and avoid assuming equal contribution of both indicators in the susceptibility index, the method of definition of the structure of the matrix was improved.
In the section "Development of a composite susceptibility index" the method used is explained as follows:

"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. Figure 3 shows the initial matrix used for the analysis. The corners corresponding to poor land cover and high morphometric indicator and good land cover and low morphometric indicator (cells a and f) were assigned a high and low susceptibility respectively, since they correspond to the extreme conditions in the analysis. The cells from b to h in figure 3 were considered to potentially correspond to any category (low, medium or high priority) and all the possible combinations of the matrix were tested assessing the proportion correct of a contingency table comparing the obtained susceptibility index and the classification of flow type from the flood records, where debris flows were considered the most hazardous type of events. Potentially 2187 combinations can be obtained by assigning the three susceptibility categories to cells b to h in the matrix shown in figure 3. Even if some combinations of the categories are not consistent with a progressive increase of susceptibility level from the bottom right corner of the matrix to the top left corner, all of them were tested. Under this procedure, the resulting matrix corresponds to the best fit of the susceptibility index and the classification of flow from flood records."

14. **Methodology. Section 2.2.3. The paper lacks a convincing comparison of the susceptibility index with actual occurrence and type of (hydro)geomorphic processes. This is a major flaw, but could be overcome by performing geomorphological mapping, e.g. from multi-temporal satellite images or in the field. (major issue)**
RESPONSE:
We agree that the validation of the proposed method is of key importance. We have responded in detail to the comment in response to the general comment.

15. **Results. Section 3.1 (p.7564, lines 15-18). You stated that "this behaviour is in agreement [: : :] where on average the watersheds in the Eastern Hills have higher local slope for a given area than in the Tunjuelo Basin watersheds". Please quantify! (minor issue)**

RESPONSE:
The quantification was added to the slope-area plot and the following paragraph was added in section "Classification of watersheds according to the debris flows propagation capacity":

"It can be observed that the segmented regression of the Tunjuelo river basin is located below the segmented regression of the watersheds located in the Easter Hills, with a difference of approximately 0.05 m/m in slope (see Figure 5)."

Additionally, the sentence was improved in the discussion, subsection Debris flow propagation, as follows:

"The analysis of the slope vs area curves shows that on average, the slope in La Chapa watershed is higher for a given drainage area than for the other considered watersheds. If the same drainage area, e.g. $1km^2$, is considered for the three watersheds with segmented regression fit shown in Figure 5, namely Tunjuelo river basin, Eastern Hills and La Negra creek, the slope values from the slope vs area curves are 0.1, 0.15 and 0.16 respectively, which means that on average for this drainage area the average local slope in the Tunjuelo river basin is milder than in the Eastern Hills with the latter being slightly milder than the local slope in La Negra creek. In the case of La Chapa watershed the value of slope for a drainage area of $1km^2$ is 0.4. This result is important 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."

16. **Discussion. Section 4.3 (p. 7572, lines 5-6). "This was considered to be due to the land cover effect on the hydrogeomorphic processes of the watersheds". Again, this is just an assumption of yours (see also comment**

13)! This could also be due a bunch of other reasons or even due to a wrong choice/weighting of parameters in your model. Please discuss more extensively/objectively. (major issue)
RESPONSE:
The sentence was deleted and the discussion was based on the results of the contingency tables and their proportion correct.

TECHNICAL/FORMAL COMMENTS

17. **Mixing of results and discussion. Please clearly differentiate between results (i.e.presentation and description of results) and discussion (i.e. the interpretation of results). (major issue)**
RESPONSE:
The results and discussion sections were modified, the presentation of results of the stages of the analysis were moved to results and the discussion section addresses only the interpretations of the results.

18. **Conclusions are far too long and inconcise. (minor issue)**
RESPONSE:
The conclusions were improved as follows:

"A susceptibility indicator composed of a morphometric indicator and a land cover indicator was used to classify the flash flood susceptibility of 106 watersheds located in the mountainous peri-urban areas of 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; with the flood type classification carried out in 11 watersheds of the study area; and assessed in three additional watersheds to those analysed in the development of the morphometric indicator. These com-

parisons were made in order to assess the appropriateness of the morphometric indicator. A susceptibility index for each of the catchments was subsequently obtained through the combination of the morphometric indicator and a land cover indicator. An important consideration during the analysis is that watersheds that are prone to debris flows are more dangerous than other flashy watersheds.
The derived susceptibility index is not absolute, but relative, and is useful in applications at regional scales for preliminary assessment and prioritization of more detailed studies. A limitation of the method is that it does not take sediment availability into account, which is a determining factor for debris flow occurrence. 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 flash flood hazard, were analysed through principal component analysis, finding that the 20 variables could be summarized in 4 component indicators related to size, shape, hypsometry and energy of the watersheds. Size of the watersheds is the component that has the highest weight in the development of the final morphometric indicator. This result is in agreement with previous research that identifies this parameter as relevant in the identification of hazard.
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 geotechnics, 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. The 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. 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 favourable morphometric conditions are present but deterioration of the watershed takes place the danger increases."

19. **Titles of sections 2.2.1 and 2.2.2. Consider using “development” instead of “construction”. (minor issue)**
RESPONSE:
Construction was replaced by development.

20. **The paper needs a spelling check (mistakes such as 4. “Discusion”). (major issue)**

RESPONSE:
A spelling check was carried out.