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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 would like to thank the anonymous referee for an extensive review of our manuscript and for providing us with helpful and constructive comments. For ease of reading we have copied the reviewer comments, as well as our response.

GENERAL COMMENTS

The article presents an index for analysing regional flash flood susceptibility purely based on information derived from digital elevation models and satellite

imagery. This index is composed by a morphometric and a land cover indicator and does require neither geological work nor field surveys. Thereby, the study is aiming at providing an approach to analyze watersheds over a large area at low time and financial requirements. While the focus is put on the development of the methodology - which is in general promising - the article would benefit from strengthening the approach used for validating the results.

RESPONSE:

As with the comment of reviewers 1 and 3 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. **p. 7555 lines 5-7 - is high susceptibility necessarily related to debris flows or can also catchments with unfavourable morphometric and land cover conditions reach high susceptibility?**
   RESPONSE: We agree that catchments with unfavourable morphometric and land use cover conditions can reach high susceptibility. To address this comment the paragraph was clarified as follows:

   "Variability in the 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. Moreover, flashier conditions, which result from unfavourable morphometric and land cover conditions, contribute to high values of the index, providing an indication of potential for flash flood danger in a large area".

2. **P. 7555, line 17: a comparison between the two approaches was carried out – how and with what objective? I propose to explain this in the methodology section. You also may want to consider that comparing two methodological approaches is relative unless you can compare with inventory information – you may want to outline how you deal with this issue.**
   RESPONSE:
   According to the suggestion in comment 13, in section 2.2 a description of the whole methodological approach was included. In this, the procedure to calculate the morphometric index and how comparisons where made are explained, as well as the objective of the methods used. The way in which different methods

were used including the comparison with inventory information (flood records) is explained in section 2.2. The following is the text that was included:

2.2 Methodology

The variability in level of hazard among clear water flows, hyperconcentrated flows and debris flows is reflected in the proposed susceptibility index, where high values represent a higher potential for debris flow and therefore an increased hazard condition. Moreover, flashier conditions, which result from unfavourable morphometric and land cover conditions, contribute to high values of the index, providing an indication of potential for flash flood danger in a large area. The proposed index to represent the level of flash flood susceptibility at regional scale is composed of a morphometric indicator and a land cover indicator. The units of analysis correspond to the watersheds delineated up to the discharge 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.

In order to develop the susceptibility index and identify if it is appropriate, a methodology that can be divided into three stages was followed. The first stage addresses the development of the morphometric indicator, the second stage corresponds to the development of the land cover indicator and the third stage is the development of the susceptibility index. Figure 2 shows the main steps that were carried out to obtain the susceptibility index for the study area.

For stage 1, a model to calculate a morphometric indicator was developed by using Principal Component Analysis on morphometric parameters that have been identified in literature as important descriptors of flood potential and debris flow discriminators. Due to the poor availability of historical records in the study area, which can limit the validation of the proposed indicator, three independent methods where used to assess the appropriateness of the morphometric indicator (methods i, ii and iii in Figure 2). The first method identifies debris flow source areas using two criteria (a and b in Figure 2) and propagates the flow on a digital

elevation model (DEM) using 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), in order to identify the capacity of watersheds to transport potential debris flows to their fans. The binary result of the propagation reaching or not reaching the fan was used to classify the watersheds. The distribution of the values of the morphometric indicator and its component indicators was analysed grouping the values according to the classification obtained from the propagation results. Furthermore, a contingency table and its proportion correct (fraction of watersheds that were correctly identified by the morphometric indicator) were used to establish the correspondence between the morphometric indicator and the classification from the propagation modelling to assess the skill of the morphometric indicator to identify the potential capacity of the watersheds to propagate debris flows.

In order to compare the morphometric indicator with field data, method ii was used (see Figure 2). A flow type classification of 11 watersheds was carried out on the basis of the available studies, reports and the flood records database managed by the municipality. The flood records database contains 55 flood events from 2001 to 2012. Due to the short period of record of the database, robust frequency analysis is not feasible. Moreover, flood records are less frequent in the Eastern Hills and non-existent in the upper Tunjuelo river basin, which may be due to the low density of population in this latter area. However, the data contained in the database normally describes affected people, type of flow and damage, and provides relevant recent historical information on the type of hydrogeomorphic processes that take place in the watersheds.

Watersheds where reports, studies or flood records clearly identify the occurrence or imminent possibility of debris flows were classified as debris flow watersheds (D), watersheds where a significant sediment concentration was identified in the past floods were classified as hyperconcentrated flow watersheds (H) and watersheds where the available reports describe the occurrence of floods without

description of sediment sources and sediment concentration were classified as clear water flow watersheds (C).
The correspondence between the morphometric indicator and the classification obtained from flood records, studies and reports in the study area was assessed through a contingency table.
The two contingency tables (morphometric indicator vs propagation classification and morphometric indicator vs flood records classification) allowed assessing the representativeness of the indicator in terms of flash flood threat level.
Additionally, the morphometric indicator was calculated for two external watersheds and a subwatershed of Chiguaza creek in the study area. This constitutes method iii in Figure 2. Since information of the dominant processes of these watersheds is available, they were used to assess the applicability of the indicator outside the study area in the first case and to add valuable information to the analysis of the study area in the second case.
A qualitative indicator of land cover was developed in stage 2, which was combined with the morphometric indicator through a classification matrix and assessed through contingency tables in stage 3 (see Figure 2).
The main input for the methods is a five-meter resolution raster DEM. This was constructed using contours that in the peri-urban area are available at intervals of 1 meter. The contours were processed to obtain a triangulated irregular network that was subsequently transformed into a raster through linear interpolation." Additionally, a clarification was included in the section propagation of debris flows as follows: *"In order to assess the validity of the MSF algorithm, the debris propagation results were compared with the extent of a well-documented debris flow event occurred in the study area."*

3. **p. 7561 line 12: You may want to explain in some more detail how you compare the results of the morphometric analysis**
RESPONSE: In the section Methodology, as presented in the response to the

previous comment, the last paragraphs were included to explain the methods used to compare the results of the morphometric indicator in more detail.

4. **p. 7562, line 26-27 Section 2.2.3 It would be beneficial to provide more details on the validation approach the subsection title is indicating. What results are you comparing and how? What is the objective?**
RESPONSE: The words "validation of results" were deleted from the title of section 2.2.3. In the subsection "Development of a composite susceptibility index" in the Methodology section, the explanation of the method to derive the index was addressed. In the previous subsections of the Methodology section, the explanation of the comparison of results was included.

5. **p. 7566-7567: While in the methodology you refer to "validation of results" the title in the results section mentions "comparison of results". This comparison seems to refer to a check with the observed flood events, however, no numbers are provided as to how many flood observations are located in catchments of what modelled susceptibility.**
RESPONSE: The term "validation" was deleted. The explanation about number of flood events was included in the methodology as well as the limitations regarding frequency due to the short time of observation of the database (see response to comment 2).

6. **Regarding the flood inventory, it would also be good if you could provide information on the robustness regarding flood frequencies. What are the reasons that you have many observations for some and no/few for other catchments? Can you use the number of observations to check against the susceptibility level you modeled? You may also want to compare the result of the susceptibility index against the result the morphometric indicator provided since you later on make the point that land cover is an important factor and should be included. I would be very interesting if you could elab-**

orate more on the last sentence of 3.4 providing more details.
RESPONSE:
Regarding the database, a description was added in the methodology as well as a comment on the limitation on frequency estimation and spatial distribution of the flood records, as follows:
"In order to compare the morphometric indicator with field data, method ii was used (see Figure 2). A flow type classification of 11 watersheds was carried out on the basis of the available studies, reports and the flood records database managed by the municipality. The flood records database contains 55 flood events from 2001 to 2012. Due to the short period of record of the database, robust frequency analysis is not feasible. Moreover, flood records are less frequent in the Eastern Hills and non-existent in the upper Tunjuelo river basin, which may be due to the low density of population in this area. However, the data contained in the database normally describes affected people, type of flow and damage, and provides relevant recent historical information on the type of hydrogeomorphic processes that take place in the watersheds."
Regarding the comparison of the result of the susceptibility index against the result of the morphometric indicator, the following paragraph was added in the discussion, subsection "Land cover indicator, composite susceptibility index and comparison of results", in order to highlight the importance of the inclusion of the land cover indicator:
"Even if the morphometric indicator provides insight in the expected behaviour and dominant processes of the watersheds reflecting the propagation capacity of the watersheds with a proportion correct of 0.56, it does not fully explain the distribution, characteristics and occurrence of the flood events in the study area. The proportion correct of the contingency matrix comparing the classification obtained from the morphometric indicator and the flow type from flood records yields a value of only 0.36. When the land cover indicator was included in the analysis on the basis that the land cover can exert a positive influence in the case of veg-

etated surfaces, but also can enhance the susceptibility conditions when urban and bare soil areas are significant, the proportion correct of the contingency matrix comparing the resulting susceptibility indicator and the flow type from flood records increased to 0.75."
In reference to the last sentence of 3.4, the analysis of the suitability of the morphometric indicator is based (in the improved version of the paper) on the comparison with flood type classification from flood records through a contingency matrix, therefore the results are explained as presented in the previous bullet.

7. **p. 7571 line 24: You may want to indicate on what observation/comparison you base this statement.**
RESPONSE: The sentence was improved as follows:
"Simplified models like MSF cannot take the influence of bridges on the propagation of the flow into account. However, independent 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, since the distance between the simulated and observed downstream limit is only 60 meters."

8. **p. 7572: I propose to strengthen this subsection 4.3 according to the name of the title. Currently the discussion seems to me rather qualitative and could benefit from a stronger analytical foundation.**
RESPONSE: Section 4.3 (Land cover indicator, composite susceptibility index and comparison of results) was improved and based on the results of the contingency tables and the proportion correct as presented in the response to comment 6.

9. **p. 7572 line 17-22: Does the flood inventory you have actually capture flood frequency well?**
RESPONSE: The limitations on frequency analysis based on the flood records are explained in the methodology according to the response to comment 6.

10. **p. 7574 line 6: You mention that the slope-area curve approach overestimates potential sources, however, can you be sure that the other methods don't underestimate? Since you don't compare to observations but between models your conclusions can only be relative I suppose.**
RESPONSE: A comparison of the sources obtained with the two methods with the photointerpretation of a zone of the study area obtained by JICA (2006) was carried out. The corresponding modification in the text of the paper is as follows:
"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. JICA (2006) identified slope failure areas related with debris flow occurrence in four watersheds located in the centre of the study area using aerial photographs from 1997 to 2004. The method applied by JICA (2006) identifies recent slope failures, old slope failures and mass movements related with potential debris flow initiation. In order to assess the initiation points obtained from the two approaches applied in this study, these were grouped into clusters where the distance between points is less than 50 m, in such a way that the clusters represent an area that produces the same propagation trajectory as the individual points. The photointerpretation carried out by JICA (2006) resulted in 108 areas of failure. The slope-area threshold procedure, correctly identified 82% of these slope failure areas with 107 clusters lying on the areas identified by JICA (2006). In contrast, the extreme event threshold correctly identified 65% of the slope failure areas with 103 clusters lying on the slope failure areas. Regarding the amount of initiation clusters identified by each criterion, the slope-area threshold resulted in 389 clusters, while the extreme events criteria identified 299 clusters. The slope-area threshold results in a false positive rate of 72%, and the extreme event threshold yields a false positive rate of 66%. The visual comparison of the initiation points is shown in figure 6. For the case of the slope-area threshold the clusters are scattered covering the mountainous area of the watersheds and even if they intersect the failure areas, the clusters cover

significant areas out of them, without showing a pattern associated to the past landslides. In the case of the initiation points from the extreme events threshold, these are not scattered on the upper watersheds but concentrated in areas from which 65% correspond to past failures. Even if the false positive rates for both methods are high the over estimated amount and distribution of initiation points in the case of the slope-area threshold procedure leads to unrealistic results when the propagation is applied with propagation areas occupying most of the area of the watersheds. Therefore, the propagation was recalculated using only the points above the curve of extreme events."

11. **p. 7574 line 28-29: "the land cover indicator improved the agreement: : :" – to what extent? Can you provide a stronger basis for this statement?**
RESPONSE:
The comparison of the results of the contingency tables (added in this version of the paper) shows the extent to which the results improve when the land cover is used. The analysis was added to the discussion as follows:
"Even if the morphometric indicator provides insight in the expected behaviour and dominant processes of the watersheds reflecting the propagation capacity of the watersheds with a proportion correct of 0.56, it does not fully explain the distribution, characteristics and occurrence of the flood events in the study area. The proportion correct of the contingency matrix comparing the classification obtained from the morphometric indicator and the flow type from flood records yields a value of only 0.36. When the land cover indicator was included in the analysis on the basis that 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, the proportion correct of the contingency matrix comparing the resulting susceptibility indicator and the flow type from flood records increased to 0.75."

TECHNICAL CORRECTIONS

12. **Abstract: The abstract is currently not indicating that the objective of the study is to propose a method for regional flash flood susceptibility assessment. Moreover, the abstract would benefit from a clearer line of thought from objective over the methodology used to achieve this objective, the results and how they relate to the objective and finally the discussion. Currently, the indicated objective is to classify susceptibility in a certain area, the approach is the use of a morphometric indicator for identifying sources and then the flow was propagated. The results show, that the morphometric indicator is insufficient to adequately assess susceptibility, so you added on the land cover. The final outcome is the understanding of the relation between morphometric characteristics and land cover.**
RESPONSE: The abstract was modified including the objective of the study as first sentence as follows:
"A method for assessing regional flash flood susceptibility at the watershed scale, based on an index composed of a morphometric indicator and a land cover indicator is proposed and applied in 106 peri-urban mountainous watersheds in Bogota, Colombia. The indicator of flash flood susceptibility is obtained from readily available information common to most peri-urban mountainous areas and can be used to prioritise watersheds that can subsequently be subjected to detailed hazard analysis.
Susceptibility is considered to increase with flashiness and the possibility of debris flows occurring. Morphological variables recognised in literature to significantly influence flashiness and occurrence of debris flows are used to construct the morphometric indicator by applying principal component analysis. Subsequently, this indicator is compared with the results of debris flow propagation to assess its capacity in identifying 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 indicators: size, shape, hypsometry and (potential) 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, providing an indication of flash flood susceptibility in the study area. The analysis shows 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 favourable morphometric conditions are present but deterioration of the land cover in the watershed takes place then the susceptibility to debris flow events increases. The indicator of flash flood susceptibility is useful in the identification of flood type, which is a crucial step in flood risk assessment especially in mountainous environments; and it can be used as input for prioritization of flash flood risk management strategies at regional level and for the prioritization and identification of detailed flood hazard analysis. The indicator regional in scope and; therefore it is not intended to constitute a detailed assessment but to highlight watersheds (which corresponds to the units of analysis) that could potentially be more susceptible to damaging flash floods than others in the same region."

13. **Methodology: You may want to consider adding details on the why and how you carried out your study as well as a clear outline of the underlying assumptions. Currently, the methodology has a strong literature review component while the explanations of the approach you actually chose and applied are rather short. E.g. the principal component analysis is mentioned in a single sentence while then in the results section information on the methodology is provided before the results are presented. I propose**

to move this information on the methodology to section 2 and in general strengthen this section. Moreover, I propose to move part of the literature review into the introduction to shorten the methodology and rather focus on describing your approach – based on the scientific basis elaborated in the introduction. It would be easier for the reader to understand the whole approach if it was explained at the beginning of 2.2. Currently, not until p. 7555 line 19 you mention the overall approach shown in figure 2 – please consider mentioning this scheme earlier in the methodology section (directly under 2.2) and explaining in detail the overall approach including underlying assumptions. It would also be helpful to clearer outline how the morphometric and the land cover indicator will be combined afterwards. Currently information on the size and extent of the inventory of past events as well as its use in the analysis process is distributed throughout the article. It would be very helpful if a detailed description was included into the methodology section.
RESPONSE: The following modifications were made:

- The explanation on principal component analysis was moved to methodology
- Part of the literature review was moved to the introduction.
- The explanation of the whole approach was included in section 2.2. This section is included in this document in the response to comment 6. with External Drift was replaced by Regression Kriging in lines 184, 599 and 636.
- The methodology was improved
- A description of the database was added in the methodology section. The text that was added is shown in the response to comment 6.

- A detailed explanation of the method to combine the morphometric indicator and the land cover indicator was added to the subsection "Development of a composite susceptibility index in the Methodology section".

14. **Section 2.2.1 Consider clearer structuring this section (e.g. with paragraph titles or an introductory sentence) since it is difficult to guess which piece of the approach you are addressing in any given paragraph. E.g. p. 7557 line 9, it comes to the reader as a surprise that you now explain the methodology regarding the second approach.**
RESPONSE: Section 2.2.1 was restructured as follows:
2.2.1 Development of the morphometric indicator
2.2.1.1 Morphometric indicator model
2.2.1.2 Propagation of debris flows
This new organisation and the text explain more clearly the approach followed.

15. **Approach 1 or 2, Approach 2a or 2b. P. 7559 line 19 you present the "second method" without having mentioned any "first method". It would be helpful if you would prior to presenting the two methods state, that two methods have been chosen, first : : : and second : : :**
RESPONSE:
To present the two approaches for debris flow initiation points identification the following paragraph was improved in the new section 2.2.1.2:
"Two of these approaches to identify potential debris flow initiation points will be used in this paper for method i in Figure 2. The first approach is based on the analysis of the break in the slope versus 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 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)."

To present the first method the following sentence was used:

"Regarding the first method of identification of debris source areas, the slope–area diagram is the relationship between the slope at a point versus the area draining through that point."...

To present the second method the following sentence was used:

"The second method that was applied to identify debris flow sources is the procedure proposed by Horton and Jaboyedoff (2008)..."

16. **Same is true for p. 7560, line 9 and 11 where the use of a certain method is stated and then the "second method" is explained.**
RESPONSE: The clarification explained in the response to comment 15 applies.

17. **p. 7560 line 16: ": : :areas that potentially could be affected by debris flow runout : : :"**
RESPONSE: It is not clear what the comment refers to.

18. **p. 7562 line 23: "... resulting indicators of morphometry and land cover were: : :" -which of the two morphometric indicators did you use?**
RESPONSE: It is expected that from the clarifications included in the methodology it is clear that there is only one morphometric indicator.

19. **p. 7562 line 25: What is the rationale behind weighting both indicators equally?**
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."

20. **Results: Consider providing a brief introduction to the section including an outline of its structure.**

RESPONSE: an introduction was added as follows:

"The results obtained for each stage of the process are presented in the following subsections. First, the results on the estimation of the morphometric indicator for the study area are presented. This section includes the development of the morphometric indicator model based on the principal component analysis and the assessment of the appropriateness of the morphometric indicator. The latter covers the classification of watersheds according to the debris flows propagation capacity and the comparison of the morphometric indicator with the propagation

of debris flows described using the MSF model, with the 11 watersheds with confirmed flow type in the study area and three additional watersheds with confirmed flow type outside the study areas. Secondly, the results of the development of the land cover indicator are shown and finally the results of the combination of the morphometric indicator and the land cover indicator to obtain a final susceptibility index are presented."

21. **p. 7563, line 3: This sentence would better fit into the methodology**

    RESPONSE: The sentence was replaced as follows:

    "The results of the principal component analysis applying a varimax rotation carried out on the morphometric variables are shown in Table 2."

    In the section "Morphometric indicator model" the following sentence has been added, explaining the extraction of morphometric parameters. This now replaces the sentence in p 7563 line 3:

    "Morphometric parameters used in literature (see Table 1) were extracted for each watershed from the digital elevation model of the study area using GIS tools."

22. **p. 7564 line 23-26: This explanation of the graph would better go into the figure caption text, not into the flow text.**

    RESPONSE: The sentence was moved to the caption of the figure. The new caption is:

    Caption: *" Slope-Area Diagram for the study area and comparative areas. This figure shows the log slope versus 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 Equation 1 and Equation 2."*

23. **P 7567, line 4-7: This information on the inventory should be provided in the methodology section.**

    RESPONSE: The description of the database was included in the methodology section as follows:

    "In order to compare the morphometric indicator with field data, method ii was used (see Figure 2). A flow type classification of 11 watersheds was carried out on the basis of the available studies, reports and the flood records database managed by the municipality. The flood records database contains 55 flood events from 2001 to 2012. Due to the short period of record of the database, robust frequency analysis is not feasible. Moreover, flood records are less frequent in the Eastern Hills and non-existent in the upper Tunjuelo river basin, which may be due to the low density of population in this area. However, the data contained in the database normally describes affected people, type of flow and damage, and provides relevant recent historical information on the type of hydrogeomorphic processes that take place in the watersheds."