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Hydrology and Earth System Sciences Discussions

Interactive comment on "Spatial variability in channel and slope morphology within the Ardennes Massif, and its link with tectonics" *by* N. Sougnez and V. Vanacker

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The comments that were made by S. Trevisani were very constructive and helped us to clarify our ideas. We feel that we have implemented all of the suggestions, and include below a point-by-point response to the specific comments.

Specific comments

P6983 line 2-5. "The development . . . " I think that the wide use of morphometric data is also related to the wider availability of topographic digital data of moderate and high resolution.

REPLY : Yes indeed, as well as the use of integrated systems to compute those datasets. The availability of multi-scale geographic data is now mentioned in the text.

P6983 line 18-20. See general comments in relation to this point.

REPLY : A new Figure has been added to the paper and shows the geological setting of the Ardennes Massif. For the analyses, we have revised all 1/50.000 geological maps that were available for the study sites to check that our knickzones not correspond with lithological contrasts or the presence of fault systems. We could observe the presence of an active fault system in the Hoëgne catchment (see geological map). However, only the tributaries and the main stream in the lowest part of the catchment have been affected by this fault system. As you can see in Figure 1b, the knickpoint that we identified is located in the upper part of the profile, and no fault has been reported for that particular location (Geukens, 1986).

P6983 line 25-29. “For these. . ..” I’m not sure about the meaning of this sentence. In particular what you mean with “hill slope processes”? While these hillslope morphogenetic processes are mainly related to uplift and not to geo-structural heterogeneity or other local factors?

REPLY : We have rephrased this section to clarify our hypothesis. In this study, we hypothesize that hillslope erosion is controlling the topographic evolution of the area after tectonic activity. Studies in other regions have shown that hillslope erosion increases with hillslope steepness and local relief. Therefore, we will test if the spatial pattern of uplift rates is reflected in the regional pattern of hillslope steepness and local relief.

P6984 line 8. Change “indices” with “morphometric indices”.

REPLY : Correction was made

P6984 line 9. I have not clear the meaning of “geomorphic response profiles”.

REPLY : We rephrased this section, and added several phrases to clarify our ideas. “We analysed possible correlation between the rock uplift pattern and slope and river

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channel morphometric indices. A multivariate spatial cluster analysis was performed to identify the morphometric indices that are most likely to represent the observed variability in slope and channel morphology. We analysed the clustering of similar morphometric values across the Ardennes Massif, and then explored possible spatial agreement between the clusters and the uplift pattern as observed by Demoulin and Hallot (2009)."

Section 2.1 Study area. I think that a simplified geo-structural map of the area should be given; this because of the geo-structural setting is, in general, a very strong factor affecting solid earth surface morphology. It could be interesting to understand how different, from this geo-structural perspective, are the selected catchments. Moreover, a more clear idea of the main river network should be given (maybe a map with the river network overlapped to a shaded relief map).

REPLY : According to this comment and the comments of Reviewer#2, a new figure was inserted. This figure shows a simplified version of the geological map of the Ardennes Massif, and indicates the hydrological network and the topographic relief of the area.

P6985 line 17-18. Here I have two questions. 1) How you can say that the climatic conditions during the quaternary were spatially uniform (i.e. what elements)? 2) If the climatic conditions have temporal variations, can we can expect that the non "steady state" character of river morphology is partially related to this change in conjunction to active tectonic?

REPLY : We have rephrased this section with the presentation of the study area. We now give more details on the climatic conditions that were present in the area since 0.65 My based on recent publications. Because of the relatively small size of the area (latitudinal extent is less than 100 km and longitudinal extent is around 150km), we hypothesize that all catchments were subjected to "rather similar" climatic conditions during the Quaternary. During the Quaternary glaciation cycles, the studied area was located outside or close to the border of the permafrost. We do not state that there was no local variability in climatic conditions within the Ardennes Massif, but we do not expect that these rather small local variability in temperature and humidity would have affected erosion process rates. It is possible that the non-steady character of the river morphology is partially related to changes in climatic conditions during the Quaternary, in conjunction to active tectonic. However, as we are focusing on spatial patterns in river and hillslope morphology in an area of spatially relatively uniform climatic conditions during the Quaternary, this does not affect the quality of our analyses. We have rephrased this section to clarify our ideas. "According to the data of Schaller et al. (2004), the Quaternary climatic cycles only had minor impacts on the high erosion rates that are observed around 0.65 My ago. Demoulin et al. (2009) also suggested that the fluvial incision of the major streams in the Ardennes Massif can be regarded as the erosional response to the tectonic uplift, while weathering and erosion processes on the hillslopes are primarily controlled by changing climatic conditions. Nevertheless, there is a paucity of quantitative data on rates of hill slope and river channel erosion to verify these different statements."

P6985 line 25. Here some points should be clarified: 1) Why only 10 catchments? According to which criteria have you chosen these basins? Could you describe shortly the "various tectonic domains" characterizing the basins?

REPLY : A similar statement on the selection of catchments was made by Reviewer #2. Here, we refer to our reply to his comments. In the description of the study area, we added a few sentences to clarify the criteria that we used for the selection of the 10 catchments. "We selected 10 catchments across the Ardennes Massif (Aisne, Bocq, Hermeton, Hoegne, Hoyoux, Molignée, Salm, Vierre, Wamme and Warche rivers) that have the same order of size (between 150 and 250 km^2) and for which consistent geological and elevation data are available. We selected rivers that are incising in the Palaeozoic substratum to avoid large lithological contrasts between the catchments." We also added a description of the uplift rates for the different catchments. "The

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catchments located in the north-eastern part of the Ardennes (Salm and Warche) have been subjected to the highest amount of uplift, whereas the catchments in the south-western part (Bocq, Hermeton, Hoyoux, Molignée) have been subjected to about half that amount. “

Section 2.2 Topographic and tectonic uplift data. This section has to be expanded and clarified; more specifically: P6986 line 7-8. “We reconstructed the original levelling curves. . .” I don’t understand the point here: if the DTM has artefacts how you can pick up correctly the levelling curves? Maybe here you mean that you re-interpolated the original levelling curves. P6986 line 9. Here I avoid to ask you why you used “topo to raster” tools but you have to say something more about the method and about the interpolation parameters that you used (this considering the topic of the special issue). P6986 line 10 The depitting method should explained better (considering that the mentioned paper is not in English).

REPLY : We have expanded this section, and now give more details on the creation of our digital terrain model and the derivation of the morphometric indices. As these comments related to the creation of the topographic data are very similar to the statements of Reviewer#2, we refer to our reply to the comments of Reviewer#2. Figure 1b. If the profiles are normalized the distance should not have the unit of measure.

REPLY : Correction was made.

P6986 line 12-13. I think that you should say that you used a D8 flow direction algorithm to derive drainage area. Then, the way in which you derived river profiles is not clear. In particular: did you derived a drainage network from the DTM? If yes, with which method (area threshold, slope area, etc. . .)? This is a very important point.

REPLY : We largely expanded this section, and now describe in much detail the methods that we used to derive the river longitudinal and transversal profiles. We used the D8 algorithm to derive drainage area. The drainage network was derived from the DTM. The area threshold was determined for each river individually based on detailed

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information on the location of the river sources that we extracted from georeferenced aerial photographs and very high resolution satellite images. We now specify this in the text.

P6986 line 25. It could be useful to remind the readers what is local relief.

REPLY : The local relief map has been generated using a 5x5 moving window (“Roving-window technique”, see also reply to comments of Reviewer#2) which calculates in the central cell, the range between the min and max values observed in the window. The local relief describes the complexity of the landscape at a larger scale than the original data and can reflect the degree of incision of an external agent (i.e. a river) (Montgomery and Brandon, 2002). We have added several sentences in the text to clarify the concept of local relief.

P6987 line 3-5. “For each catchments ..” The procedure followed to pick up longitudinal and transversal profiles is not clear (this also in relation to the comment on river network derivation). What you mean when you say “based on original levelling curves”? Did you not used the derived DTM?

REPLY : We clarified this issue in the text : For the extraction of the longitudinal profiles, we used the contour lines that we reconstructed from the DTM provided by the IGN. This information (reconstructed contour lines) better represents the original topographic data, and is not affected by any interpolation artefacts. This was particularly useful for the reconstruction of the topography of the river valleys, as the spacing between the contour lines is often very irregular in these areas. For the extraction of the transversal profiles, we used the information from the DTM that we interpolated from the reconstructed contour lines. The spacing between the contour lines is more regular on the hillslopes, and the transversal profiles are less affected by any possible artefacts resulting from DTM interpolation.The transversal profiles were directly derived from the DTM, and using the 3D Analyst ArcGis extension. This tool draws a 3D shapefile line and extracts the value of every cell this line comes across.

P6987 line 14. I think that it is a matter of taste but from my side I prefer “downstream distance” to “distance to source”.

REPLY : Ok. We replaced this by ‘upstream distance’.

P6987 line 14 -22. The discussion on knickpoints is very important considering that part of your conclusions is based on these features. You should explain how you selected the knickpoints of tectonic origin and discarded the ones related to geo-structural heterogeneity or other factors.

REPLY : The knickzones were identified based on the slope-area diagrams. Any abrupt change in channel slope gradient for a given drainage area was identified as a knickpoint. We then checked for every knickpoint the possible existence of a lithological contrasts that could have caused this change in channel gradient. We used the geological maps at 1/50.000 scale of the area to check for any strong lithological contrasts. Given the fact that we explicitly selected the ten catchments in the Palaeozoic basement rocks only, we already excluded the possible influence of very strong lithological contrasts between metamorphic and sedimentary rocks. This is now clarified in the text.

P6988 line 5–8. Viewing the things from a geological perspective, I think that channel steepness represents the balance between net uplift and erosion only in particular conditions (i.e. in absence of geo-structural heterogeneity, local oscillations of base level, etc. . .).

REPLY : We agree with Reviewer#3 that the tectonic imprint on the river channel morphology is far more difficult to discern in areas with geostructural heterogeneity, local oscillations in base level and/or climatic conditions. We have added a sentence to the text to indicate this perspective.

Section 2.4 Statistical analysis. This section should be expanded and explained. See reply to Reviewer1. We now give more details on the type of statistical analyses that

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we have used in our study. In order to classify the catchments 'objectively' according to their different properties, a multivariate statistical classification method has been chosen. We preferred to use an unsupervised classification method, such as the K-mean clustering method.

P6990 line 12. "within" Could you say more about the morphological heterogeneity characterizing the single catchments?

REPLY : We have rephrased this sentence, as this was not entirely clear. Based on our analyses, we do see large differences in slope and channel morphologies between the different catchments. There exists morphological heterogeneity within most of the catchments, as clear knickzones are present. We do specify this in the second and third paragraph of the section 'results', and discuss this even in more detail later (P. 6993, and Figure 5).

Section "3 results" and "4 discussion": 1) I think that dividing 10 samples (the 10 catchments) in 3 classes could be questionable. This in the sense that for defining the characteristics of each cluster you have only 3 or 4 samples. But 4 samples are few for calculating also simple statistical moments such as the mean or the standard deviation. Then, looking at table 2, I'm wondering if you normalized data before performing the clustering.

REPLY : See reply to comments of Reviewer1. It is clear that it would have been better to use a larger number of observations to have robust results from the statistical analyses. For this study, we were limited by the small size of the study area and the rather limited number of catchments that fulfilled our selection criteria. We give more details on our selection criteria in the text; and also added a few sentences to the discussion. We did normalize our data before performing the clustering. This information was added to the text.

2) Figure 2b and text at pages 6990-6991. Is not clear if and why you excluded from the regression the points inside the circles. Then how do you derived Figure 2d?

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REPLY : Concerning Figure 2b, the regression has been calculated only for the six catchments that are not circled. A negative linear regression between SCI and MU values was expected but two spots of low concavity (or high convexity) and low uplift can be delineated (the more a catchment is located in an uplifted region, the more his profile is convex). Any geological contrast or fault presence can explain the convexity of these profiles. Only a local tectonic subduction zone located in this region (actually the river concerned are located in the same area) could explain this situation. This explanation has not been confirmed by other studies but the update of the Belgian geological map in 2013-2015 will maybe give more insights on that topic. The regression equation has been removed to not confuse the readers. The same question about the Slope-Area graphic (Figure 2d) has been asked by the Reviewer#2: This graph was constructed with the flow accumulation raster1 (see also comment of S.Grimaldi on that topic), as well as the average slope of several river segments. Each river was divided into several segments, delimited by the intersection of the river track line and the contour lines of the landscape. The drainage area (x axis) has been calculated at every intersection with the contour lines (every meters) using the flow accumulation raster, and the slope (y axis) is actually the gradient to the next intersection (and correspond to one meter divided by the flow path distance to run it down). The relations between A and S are typically following a negative power function, and are commonly represented on a log-log graph (this explanation has been added to the text). All the catchments have been considered in this graphic.

3) Figure 4. I have the feeling that the number of catchments are too few to justify a quadratic polynomial relation.

REPLY : We agree with this statement. The number of catchments (10) is limited, and too few to justify a quadratic polynomial relation. In fact, the polynomial curve that was shown in Figure 4 was intended to be suggestive to indicate the non-linear relationship that we observed between HI and Rch. We have removed the equation and the R2 from the Figure.

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Section 5 “Conclusions”. In regard to the conclusion that the river morphological properties are better indicator of recent tectonic activity than the morphometric parameters of hillslopes should discussed in more detail. This because of the limited resolution of the dtm used as well as the limited number of indexes you use to pick up the morphology of hillslopes. I'm wondering if the same happens if you use higher resolution dtm and/or other morphometric indexes such as roughness or indexes related to channel network density. Another conclusion of your paper, from my point of view, is that in this case an index based on expert knowledge (i.e. the selection of knickpoints) seems to fit better with uplift data than “automatic” calculated indexes. In particular, the selection of knickpoints is mainly based on expert knowledge and on a visual analysis of longitudinal profiles; differently, the other morphometric indexes are calculated automatically and objectively (well, neglecting the subjective choice of calculation parameters) from the dtm. Makes sense to put together in the analysis these two family of indexes?

REPLY : A higher resolution DTM has been tested in the studied area: A LIDAR (Light Detection And Ranging) DEM data of 1m resolution has been used in the Hoëgne catchment for the extraction of Transversal and Longitudinal profiles. An important amount of human induced artefacts have appeared in the profiles (roads, bridges, buildings, trees, etc.), and both automatic and manual removal could not completely remove these artefacts. Moreover, these objects often form artificial barriers that block or force the flow calculations. Therefore, we decided to work with the DTM of 20 meters resolution that is a good compromise between a coarse resolution (i.e. 50 m resolution DTM) that can skip some morphological features, and a very detailed elevation model (such as the LIDAR DEM) that can distort the calculations due to artefacts. We are aware that other morphometric indexes could have been calculated. In this paper, we tried to use a wide variety of indexes that exactly belong to different families. Our analysis is based on channel related indexes (i.e. the river longitudinal profiles or the stream concavity index), catchment-wide indexes (i.e. Horton or the Hypsometric Integral), and also on indexes that are based on expert knowledge (i.e. the interpretation of geologic maps for the identification of knickpoints). These different aspects of the

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morphology of the hillslopes and channels are closely related and we assumed that it is important to take different hillslope, channel and catchment-wide metrics into account for the analysis of multiple landscape components.

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