Spatial Variability in Channel and Slope Morphology within the Ardennes Massif, and its Link with Tectonics

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1. Introduction

There is great interest across a broad spectrum of geoscience disciplines in unravelling the role of tectonic activity in accelerating erosion processes and landscape evolution (Burbank et al. 1996, Maddy 1997, Vanacker et al. 2007). Surface processes that produce and transport sediment, and incise river valleys are complex; and difficult to quantify at longer timescales of 10^3 to 10^5 years. In this research, we analyze spatial variation in channel and slope morphology for low relief terrain with differential uplift rates. We specifically test if we can deduce the landscape response to tectonic activity based on the present-day channel and slope morphology. For these transient landscapes, we hypothesize that the channel morphology is a better indicator of landscape response than the hillslope form and relief.

The Ardennes Massif is an excellent field site for studying these processes. The area has been subject to differential tectonic movement: the Northeastern part of the Massif is characterized by moderate uplift and seismic activities, whereas the western and southern parts are undergoing only slight epeirogenic upheaval (Pissart 1974, Demoulin 1995, Meyer and Stets 1998, Garcia-Castellanos et al. 2000, van Balen et al. 2000). Various morphometric indices were used and developed to capture the specific slope and channel morphology of the basins. We then analysed possible correlation between these indices, lithology, and tectonic activity.

2. Material and Methods

We selected 10 catchments of about 150 to 250 km^2 across the Ardennes Massif (Fig. 1: Aisne, Bocq, Hermeton, Hoegne, Hoyoux, Molignée, Salm, Vierre, Wamme and Warche rivers). Most catchments are third order basins belonging to the Meuse River Basin. They cover various tectonic domains with uplift rates ranging from about 15 to 200 mm/kyr since mid-pleistocene times according to van Balen et al. (2000).

Our morphometric study is based on the Digital Elevation Model (DEM) produced by the Belgian National Geographical Institute (IGN/NGI). We used the DTM-1:10.000 product that is developed from photogrammetric derived levelling curves. This product is a regular grid of data points at 20 m resolution, and is reported to have RMS errors between 0.5 and 1.25 m horizontally and 1 and 1.6 m vertically. Due to interpolation artefacts in the original dataset, we were obliged to reconstruct the initial levelling curves (5 m equidistance) from the digital elevation data. We interpolated these contourlines using the "Topo to Raster" ArcGis function to obtain a continuously varying 3D surface. The DEM was then hydrologically corrected using the sink-fill method presented in Schäuble (2000).

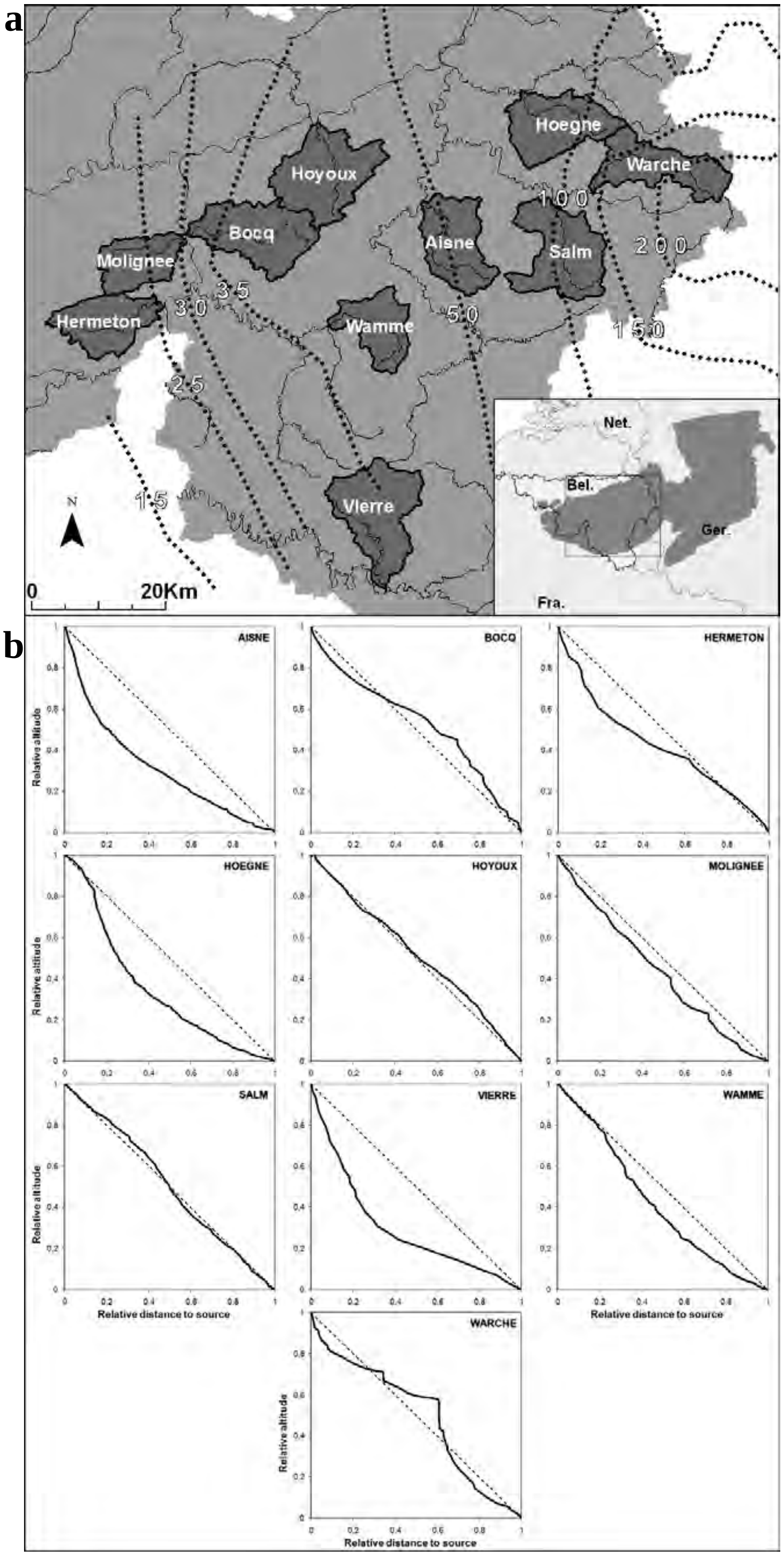

Figure 1**a.** Location of the 10 catchments in the Ardennes-Rhenish Massif (inset map). The dotted lines correspond to the uplift isolines (mm/kyr) from the studies of Meyer and Stets (1998) and van Balen et al. (2000), and were derived from terrace sequences.
b. Normalised longitudinal profiles of the selected rivers.

First, we derived simple morphometric indices that capture the overall slope morphology. Classical morphometric indexes (index of Gravelius, Shumm and Horton) were extracted to compare the overall geometrical shape between the catchments. The indexes of Schumm and Horton have the advantage of not being scale-dependent, which is not the case for the index of Gravelius that proved to be highly raster resolution dependent (Sanadeera et al. 2004). To get an insight in the spatial distribution of the slope morphology within the catchments, slope and local relief maps were made (with local relief here defined as the relief in a 100 m range moving window).

Second, we focused on the river channel morphology. For each drainage basin, we extracted the longitudinal river profiles and several transversal profiles based on the original levelling curves. The transversal profiles were measured perpendicularly to the river and between tributaries confluences to avoid the lowering of the slopes in such cases. For each river, more than 20 transversal profiles were extracted using the ArcGis 3D Analyst Function. The 8 most representative profiles with minimal effect of anthropogenic artefacts (such as roads, reservoirs, or villages) were then selected for analysis. Stream proximal slope (S_k in %) and curvature (C_k) were calculated using the following equations:

$$S_i = \frac{(y_{i-1}) - (y_{i+1})}{(x_{i-1}) - (x_{i+1})} \cdot 100 \tag{1}$$

$$C_i = \frac{\left(\frac{(y_{i+2}) - (y_i)}{(x_{i+2}) - (x_i)}\right) - \left(\frac{(y_i) - (y_{i-2})}{(x_i) - (x_{i-2})}\right)}{(x_{i+2}) - (x_{i-2})} \tag{2}$$

with x_i = distance to source (m), and y_i = altitude (m) at point i.

Slope-Area diagrams were constructed to help us to identify knick zones. For each river, we fitted an inverse power law equation (so-called Flint law) between the drainage area (A) and the channel gradient (S):

$$S = k_s A^{-\theta} \tag{3}$$

The empirically derived parameters k_s and θ are indicators of the steepness and the concavity of the longitudinal river profile (Hack 1973, Whipple 2004). A comparison of the observed Slope-Area relationships for the 10 rivers in the Ardennes Massif allows us to compare the channel morphology of rivers draining highly different tectonic regimes. As the empirically derived value of the steepness index k_s is dependent on the profile concavity, we normalised the steepness to a reference concavity, θ_r, of 0.45 following Howard (1994) and Whipple and Tucker (1999).

In addition to these parameters, we derived the Stream Concavity Index (*SCI*) of each river channel as defined by Demoulin (1998). The form of the river channels in the Ardennes Massif is highly variable, and some rivers display clear convexities (Fig. 1b). In this low-relief terrain, the stream concavity index can be used as an index of transient response to tectonic uplift. The SCI is a measure of the surface between the normalised longitudinal profile and a straight line joining the source and the outlet of the catchment (Equation. 4):

$$SCI_i = 1 - \sum_{i=0}^{1} \left((x_i - x_{i+1})(y_i + y_{i+1}) \right) \tag{4}$$

with x_i = distance to source (m), and y_i = altitude (m) at point i.

Third, we analysed the hypsometry of the catchments to get a measure of the overall slope and channel morphology. The hypsometric integral, *HI*, was calculated as follows:

$$HI_i = \sum_{i=0}^{1} \frac{1}{2} (y_{i+1} + y_i)(x_{i+1} - x_i) \tag{5}$$

where x_i = distance to source (m), and y_i = altitude (m). As our catchments have similar size, the scale-dependency of the hypsometric integral should not affect our results. The hypsometric integral is a measure of the distribution of landmass volume above a basal reference plane, and can be interpreted in terms of relative landform age (Strahler 1952). Differences in the shape of the hypsometric curve can be related to differences in erosive and tectonic processes (Luo 1998, Weissel and Pratson 1994).

3. Results and Discussion

Our morphometric analyses indicate that large differences exist in morphology both within and between the selected catchments. Based on our observations, we identified three broad 'morphological' groups (S1, S2, S3; in Fig. 2). The slope and channel morphology of these groups can be interpreted in terms of adjustment of the topography to relative base level change following uplift (Fig. 2).

The first slope and channel morphology group (S1) is typical for catchments that are located in the upper part of the catchments where smooth channel-to-hillslope transition could be observed. This morphology was mostly observed for plateau positions, and corresponds to alluvial stream systems where slope and channel processes are coupled.

The second and third group are transitional systems. The S2 scheme is characterized by very high constant slopes close to the rivers and by a rapid transition to flat slopes. This scheme is typical for knick zones with a decoupling of channel and slope processes. The S3 scheme (smooth S-curved slopes) can be seen as the later stage of evolution of the S2 scheme with the development of a large valley plain and with highest slope gradient located in the middle part of the slopes. We found this S3 scheme often in the downstream part of the catchments, and it corresponds to recent rejuvenated topography.

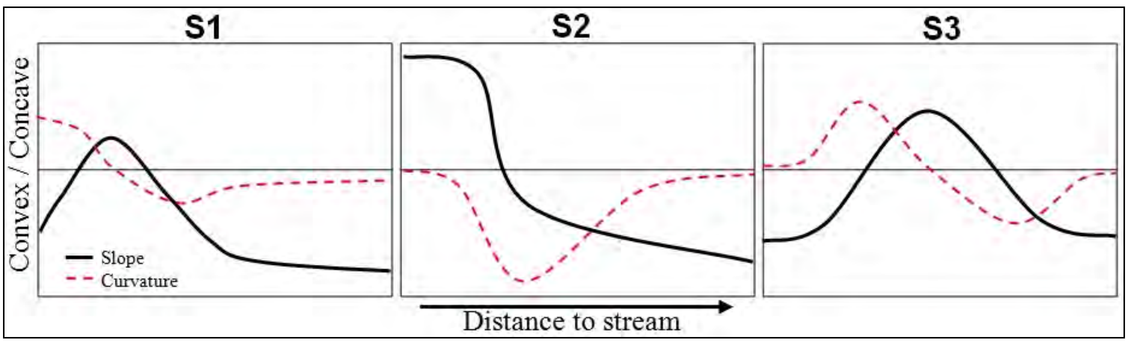

Figure 2. Schematic illustration of the Slope/Curvature evolution along the streams.

The observed variability in slope and channel morphology broadly coincides with the regional differences in tectonic and seismic activity that were reported by Meyer and Stets (1998) and van Balen et al. (2000). The catchments in the western and southern part of the Ardennes Massif are more prone to have relatively smooth river and channel profiles, although various exceptions exists. In the Northeastern part of the Ardennes Massif, we observed various catchments with irregular 'non-equilibrium' slope and channel profiles, and the presence of clear knickzones.

We specifically tested the correlation between the slope and channel morphology and the regional tectonic differentiation patterns. The Mean Uplift Rate (*MUR*) for each catchment was derived from van Balen et al. (2000). In addition to the morphometric indices that are described above, we calculated two parameters that are linked to the position of the knickzone: *Cha* and *Chr*, respectively the absolute and relative position of the principal stream convexity (above sea level or above catchment outlet). Table 1 summarizes the morphometric parameters for each river catchment.

Rivers	*S* (km²)	*P* (km)	*MUR* (mm/kyr)	*Cha* (m a.s.l.)	*Chr* (m)	*ho* (m a.s.l.)	*Gr* (-)	*Ho* (-)	*Sc* (-)	*θ* (-)	*Ksn* (-)	*HI* (-)	*SCI* (-)
Aisne	190,6	71,0	70	450	315	135	1,439	0,441	0,750	0,478	44,45	0,251	0,379
Bocq	235,4	89,0	40	195	100	95	1,624	0,341	0,659	0,478	11,87	0,523	-0,055
Hermeton	169,3	69,6	22,5	150	50	100	1,498	0,316	0,635	0,323	13,25	0,442	0,165
Hoegne	208,6	75,1	120	510	375	135	1,456	0,356	0,673	0,552	72,19	0,221	0,316
Hoyoux	255,7	94,6	45	200	125	75	1,656	0,570	0,852	0,017	26,15	0,481	0,002
Molignée	139,3	58,5	30	150	60	90	1,388	0,384	0,699	0,138	18,77	0,376	0,145
Salm	238,0	90,3	162,5	460	210	250	1,640	0,423	0,734	0,052	24,39	0,422	-0,002
Vierre	259,1	89,2	42,5	330	10	320	1,551	0,374	0,690	0,519	13,62	0,263	0,408
Wamme	140,2	68,8	45	430	245	185	1,627	0,440	0,748	0,196	38,93	0,308	0,178
Warche	191,2	94,7	180	522,5	222,5	300	1,918	0,245	0,558	0,513	11,12	0,484	0,011

Table 1. Computed rivers parameters: *S* = Surface; *P* = Perimeter; *MUR* = Mean Uplift Rate; *Cha* and *Chr* = the absolute and relative height of the convexities (in meters); *ho* = the altitude of outlet; *Gr*, *Ho* and *Sc* = the classical morphometric indexes (Gravelius, Horton and Shumm); θ and *Ksn* = the Convexity and Normalised Steepness indexes (Flint law); *HI* = the hypsometry integral; and *SCI* = the Stream Convexity Index.

Our data show some correlation between the overall catchment morphology and tectonic activity. First, a nonlinear relation was observed between the hypsometric integral, *HI*, and the relative position of the stream convexity, *Chr* (Fig. 3). This observation is related to the upward migration of knick zones in the catchments. We broadly identified three types of catchments (Fig. 3). The first channel morphological type (low *HI*, and low position of the convexity) broadly corresponds to river basins with equilibrium long profiles. Three river basins (Vierre, Hermeton, and Molignée) in the upper part of the Meuse catchment have such a channel morphology, and seem not yet affected by the base level changes following the uplift of the Ardennes Massif. The second type (high *HI*, medium relative height of convexity) contains catchments that were subject to recent tectonic activity (Bocq and Hoyoux) or that had higher tectonic uplift rates (Warche and Salm). The rivers that are draining regions with weak lithologies and/or long incision history appear in the third group.

This theoretical model indicates that the hypsometric integral (HI) is not adequate to determine the adaptation stage of a river profile. A river with a low hypsometric integral may either have been formerly crossed by a tectonically-driven knickpoint, or have not yet been affected by the uplift and thus remained in equilibrium state.

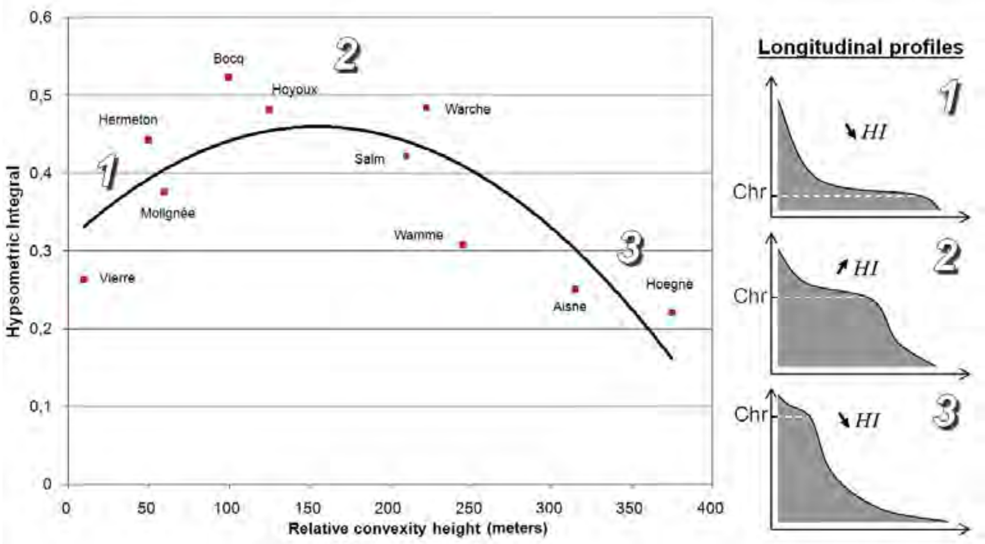

Figure 3. Nonlinear relation between the relative convexity height (*Chr*) and the hypsometric integral (*HI*).

Second, we observe that the absolute height of the river channel convexity is related to the mean uplift rate: catchments that are located in regions with higher uplift rates generally have knickzones at higher altitude (Fig. 4). This relationship may seem self-evident, as the mean elevation in the catchment can be expected to be directly related to the total uplift. However, this observation also shows that knickpoints do not dissipate rapidly in low relief terrain with low to moderate uplift rates.

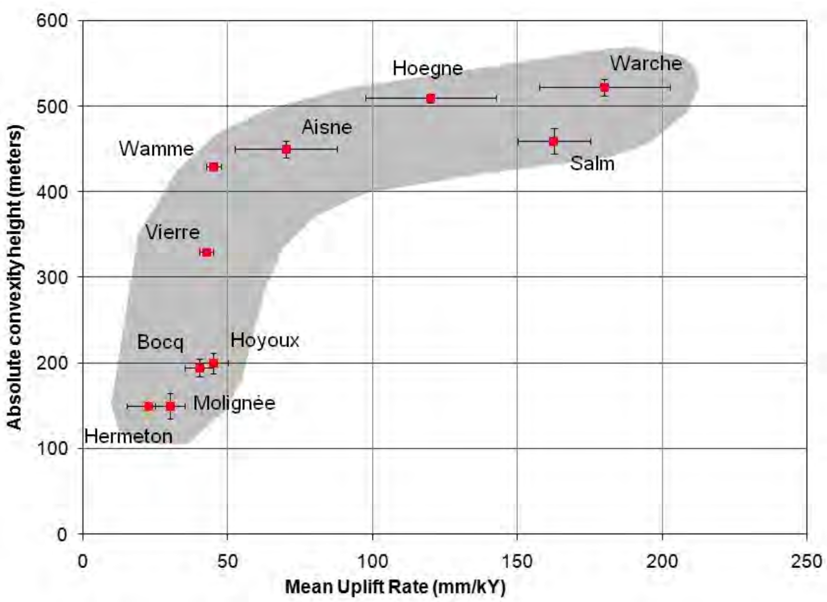

Figure 4. Relation between the *MUR* and the *Cha* parameters for the selected catchments. Errors bars are represented according to the position of the uplift isolines inside the catchment and to the position of the knickpoint into the longitudinal profile.

We observed some correlation between the Mean Uplift Rate of the catchments and the Stream Concavity Index (Equation. 4): catchments with concave upward river profiles are generally located in zones with low uplift rates (Fig. 5). However, convex reaches are not necessarily associated with zones with high uplift rates. This might partially be explained by the presence of local lithological contrasts, but might also be associated with local tectonic activity (Bocq and Hoyoux catchments, located close to centre of subsidence of Namur). The latter is currently under study, and is known as being poorly represented in the data of van Balen et al. (2000).

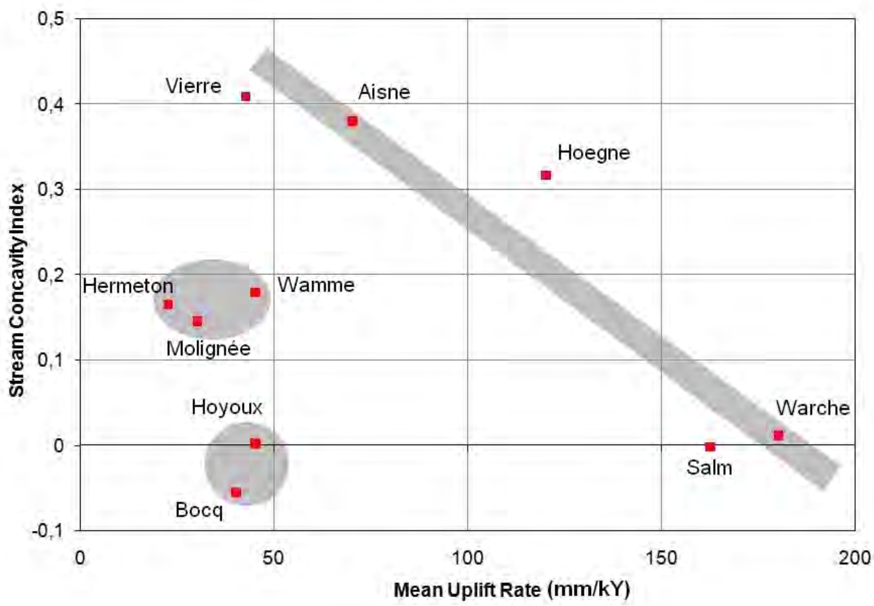

Figure 5. Stream Concavity Index (*SCI*) vs. Mean Uplift Rate (*MUR*).

Finally a *K*-means cluster analysis was performed on several variables to catch the spatial pattern in slope and channel morphology and see the relations with the differential tectonic activity. A reduced number of variables were selected to avoid redundancy in the analysis: *Chr*, *Gr*, *Ho*, *Sc*, θ, *HI*, *ksn* and *SCI*. Table 2 shows the main characteristic of the three clusters that were recognized by the statistical procedure:

	Rivers	*Mean Chr*	*Mean Gr*	*Mean HI*
Cluster 1	Salm, Wamme and Warche	255.83	1.72	0.40
Cluster 2	Aisne and Hoegne	345	1.44	0.23
Cluster 3	Bocq, Hermeton, Hoyoux, Molignée and Vierre	69	1.54	0.42

Table 2. Results of the clustering analysis and mean values of the three main parameters.

The clusters cover different tectonic domains in the Ardennes Massif (Fig. 1a). The first and second cluster contain rivers that are draining the most uplifted part of the Ardennes Massif, while the third cluster contains all Condruzian Rivers and the Vierre which is located in the Semois system. In a slope-area diagram (Fig. 6), the three clusters cover different domains. The first cluster is characterized by a low concavity index (θ = 0.34) opposed to reference concavities of θ = 0.43 and 0.45 for the 2nd and 3rd cluster resp. The two clusters (cluster 2 and 3) are clearly different in steepness value.

This observation clearly shows that variations in channel and slope morphology between the basins are not only reflecting differential uplift rates, but also the transient response of the basins to relatively base level lowering following uplift. Our data seem to suggest that relative base level lowering of the Meuse River is the driving force of river incision in the Ardennes Massif, and that a transient signal of adjustment is migrating through the Meuse basin. This hypothesis is conform with recent measurement of terraces by Rixhon et al. (2009). Rivers that are hydrologically more distant from the Meuse River are more likely to be in transient state, as the knickzones have not yet propagated to the upper parts of the river network.

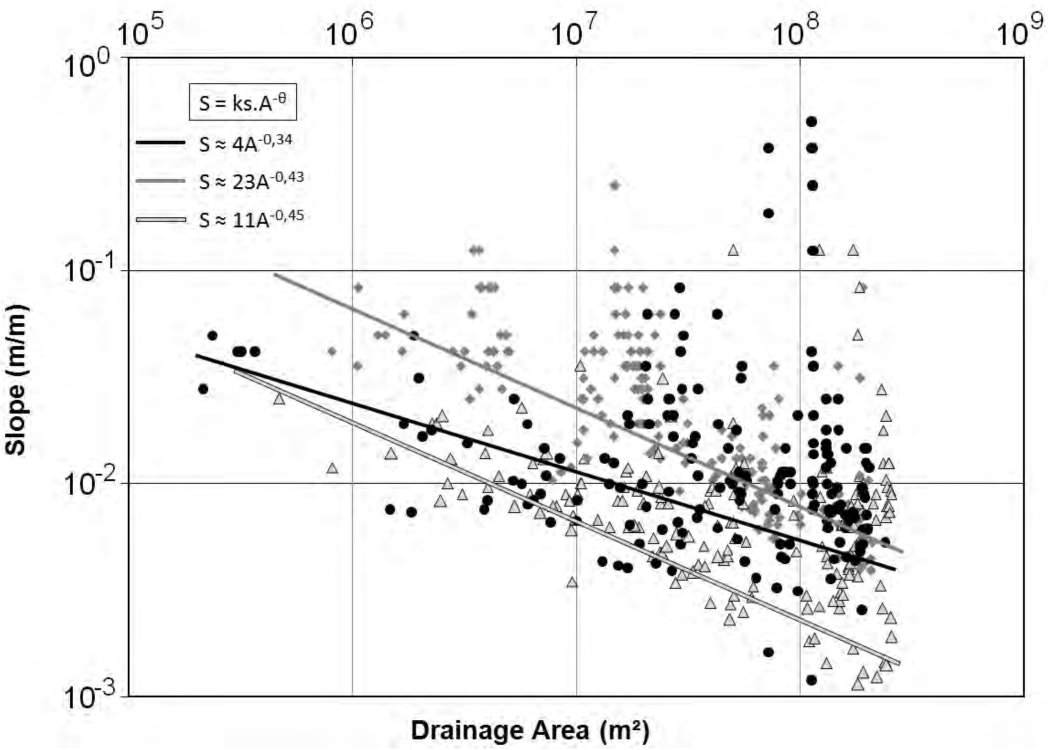

Figure 6. Illustration of the three Cluster groups within the Slope-Area space. The black dots represent the first cluster (Salm, Wamme and Warche Rivers), the grey diamonds represents the second cluster (Aisne and Hoegne), and the white triangles the last cluster (Bocq, Hermeton, Hoyoux, Molignée and Vierre Rivers).

4. Conclusion

Our morphometric analysis of 10 catchments in the Ardennes Massif indicates that slope and channel morphology is often an indicator of transient adjustment of rivers to tectonic uplift. Whereas there is some general agreement between some of the overall morphometric parameters and the mean uplift rates for the Ardennes Massif, the detailed picture is far more complex and some metrics appear to be insensitive to differential tectonic uplift.

It is clear that further research is needed both on the rates and patterns of tectonic evolution of the Ardennes Massif and on improved morphometric indices of local slope and channel morphology to fully elucidate the tectonic imprint on the landscape.

Acknowledgments

This study is part of a PhD research project that deals with the link between topography, tectonics and erosion in the Ardennes Massif. This project is financed by a FSR grant to VV.

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