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Delineating riparian zones for entire river networks using geomorphological criteria

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Abstract

Riparian zone delineation is a central issue for riparian and river ecosystem management, however, criteria used to delineate them are still under debate. The area inundated by a 50-yr flood has been indicated as an optimal hydrological descriptor for riparian areas. This detailed hydrological information is, however, not usually available for entire river corridors, and is only available for populated areas at risk of flooding. One of the requirements for catchment planning is to establish the most appropriate location of zones to conserve or restore riparian buffer strips for whole river networks. This issue could be solved by using geomorphological criteria extracted from Digital Elevation Models. In this work we have explored the adjustment of surfaces developed under two different geomorphological criteria with respect to the flooded area covered by the 50-yr flood, in an attempt to rapidly delineate hydrologically-meaningful riparian zones for entire river networks. The first geomorphological criterion is based on the surface that intersects valley walls at a given number of bankfull depths above the channel (BFDAC), while the second is based on the surface defined by a threshold value indicating the relative cost of moving from the stream up to the valley, accounting for slope and elevation change (path distance). As the relationship between local geomorphology and 50-yr flood has been suggested to be river-type dependant, we have performed our analyses distinguishing between three river types corresponding with three valley morphologies: open, shallow vee and deep vee valleys (in increasing degree of valley constrainment). Adjustment between the surfaces derived from geomorphological and hydrological criteria has been evaluated using two different methods: one based on exceeding areas (minimum exceeding score) and the other on the similarity among total area values. Both methods have pointed out the same surfaces when looking for those that best match with the 50-yr flood. Results have shown that the BFDAC approach obtains an adjustment slightly better than that of path distance. However, BFDAC requires bankfull depth regional regressions along the considered river network. Results have also confirmed that unconstrained valleys require lower threshold values than

constrained valleys when deriving surfaces using geomorphological criteria. Moreover, this study provides: (i) guidance on the selection of the proper geomorphological criterion and associated threshold values, and (ii) an easy calibration framework to evaluate the adjustment with respect to hydrologically-meaningful surfaces.

1 Introduction

Riparian vegetation is involved in different geomorphological, hydrological and ecological processes (Tabacchi et al., 1998; Naiman et al., 2005) and provides many services to society, such as reducing flood risk or improving the availability and quality of water (Staats and Holtzman, 2002; Hruby, 2009). Despite this, riparian zones are commonly under high pressure due to human activities and land-use transformation (for a review see Poff et al., 2011). The maintenance of riparian functions and values is of key importance and requires planning at catchment scale and to locate the optimal zones to conserve or restore riparian buffer strips. Additionally, the definition of riparian zone extent is an unavoidable issue when managing river corridors. There are however, several different approaches to delineate riparian areas and consensus is still far from being achieved.

The delineation of riparian zones is highly dependant on what is understood as "riparian". Existing definitions are quite heterogeneous with respect to the zones encompassed by this term. While most authors use definitions matching with river banks and floodplains, others also include river channels (Naiman et al., 1993; USDA FS, 1994) or extend these zones to the slopes adjacent to floodplains (Ilhardt et al., 2000; Verry et al., 2004). By focusing on land adjacent to watercourses, there is agreement about the following riparian zone characteristics: (i) they are transitional zones between aquatic and terrestrial ecosystems (Gregory et al., 1991; NRC, 2002), (ii) their soil and vegetation characteristics are strongly influenced by free or unbound water in the soil that comes from elevated water tables and flooding by high waters (USDA NRCS, 1991; Naiman et al., 1993; USDA FS, 1994), (iii) they present sharp gradients of environmental factors, ecological processes and biota (Gregory et al., 1991; NRC, 2002). As an ecotone, riparian zone limits are fuzzy and defining discrete boundaries can be a difficult task. In addition, the extent of the riparian zone is not constant within the longitudinal dimension of rivers, nor follows a well-established increasing gradient from source to mouth. Instead, riparian vegetation responds to the array of hydrogeomorphic patches appearing along the fluvial network (Van Coller et al., 2000; Poole, 2002; Thorp et al., 2006), being influenced by the external disturbance regimes of floods and landslides (Gregory et al., 1991) and also by channel confluences (Benda et al., 2004).

As Yarrow and Marín (2007) suggest, a compromise is made when we move from theoretical to operational definitions. Establishing fixed distances from water edge has been a common approach in riparian delineation for regulatory purposes (e.g. best management practices, Australian Rivers and Foreshores Improvement Act, Canadian Streamside Protection Regulation), with buffer widths ranging habitually from 10 to less than 50 m. In this regard, 40 m is suggested by some authors as the width that accomplishes most riparian functions (Sutula et al., 2006, Clerici et al., 2011). However, other authors point out the maintenance of wildlife at that width is only assured for aquatic species, but do not encompass the zone of primary activity of amphibians and terrestrial species (Pearson and Manuwal, 2001; Hruby 2009). Moreover, headwater streams have been suggested to require much narrower buffer strips to ensure amphibians support (Perkins and Hunter, 2006). In this line, fixed buffer approaches often result in oversized riparian areas in headwaters and confined valleys and undersized in lowlands and unconfined valleys (Holmes and Goebel, 2011). Some authors have dealt with this issue by establishing a buffer distance dependant on river order (e.g., Yang et al., 2007), although this approach is still not sensitive to local geomorphology as a river of a given order can show large valley morphology variability. Recent approaches are setting aside fixed buffers and moving forward to more-objective criteria. Some of these criteria are based on physical attributes, such as soil characteristics (Palik et al., 2004) or hydrology (Hupp and Osterkamp, 1996; Osterkamp and Hupp, 2010). Others are based on biological communities, such as vegetation (Amundsen, 2003; Mac Nally et al., 2008) or amphibians (Perkins and Hunter, 2006). Most of these criteria demand information that is not usually available over large areas, or not with enough spatial resolution to delineate riparian areas. Besides, they are usually applied to definite linear boundaries without accounting for the environmental gradients existing within riparian zones. Instead, Clerici et al. (2011) have developed a GIS-based riparian zonation model which uses membership scores indicating the probability of belonging to the riparian zone based on natural vegetation presence and water influence.

Riparian vegetation communities have different composition and phenologies than those present in upland zones, and their spatial and temporal distribution is heavily influenced by flood regime (Merrit et al., 2009; Naura et al., 2011). High flows (characterised by magnitude, duration and frequency) control the creation and destruction of landforms across the fluvial landscape, and limit the spread of non-riparian species (Merrit et al., 2009). Consequently, flood recurrence interval may be an objective approach to delineate the outward boundary of the riparian zone. In this regard, the 50-yr flood has been indicated as an appropriate hydrological descriptor for riparian zones as it usually coincides with the first terrace or other upward sloping surface (Ilhardt et al., 2000). Moving outward this topographic boundary necessarily increases water table depth and the probability of finding vegetation species related to riparian ecosystems may rapidly decrease. Deriving the surface covered by a flood of a given recurrence interval, however, requires long series of flow data (failing that, it requires long series of precipitation data and information about catchment response to precipitation) and valley and channel cross-section data at many locations. This issue can be solved using geomorphological criteria potentially related to hydrology. Geographical Information Systems (GIS) allow the application of these geomorphological criteria over large areas from few easily-available inputs (e.g., Digital Elevation Model; DEM). Unfortunately, there are not many published works dealing with this issue and the existing ones follow different methodological approaches (e.g., Sutula et al., 2006; Abood and Maclean, 2011; Clerici et al., 2011). Hence, guidance about the choice of a proper geomorphological threshold value defining riparian extent is still difficult to find. Here we explore the adjustment of two geomorphological criteria, the number of bankfull depths above the channel (BFDAC) and the path distance, with respect to the 50-yr flood in a GIS environment. This is intended to rapidly delineate hydrologically-meaningful riparian zones for entire river networks. As the relationship between local geomorphology and 50-yr flood has been suggested to be river-type dependant (Rosgen, 1996) we have performed the analyses distinguishing between three river types corresponding with three valley morphologies: (i) open valleys, (ii) shallow-vee valleys and (iii) deep-vee valleys and gorges. We have also compared the performance of two different methods to evaluate adjustment between the surfaces derived from geomorphological and hydrological criteria. One of them is based on exceeding areas (minimum exceeding score) and the other on the similarity among total area values.

2 Material and methods

2.1 Study area

This study was developed in river catchments from the Cantabrian region, Northern Spain. Only river stretches with no flood restrictions for which flood data (specifically, surface flooded by the 50-yr flood) was available have been included in the study (Fig. 1). Cantabrian rivers have their source in the Cantabrian Cordillera, a mountain range which runs parallel to the Atlantic Ocean coast and reaches up to 2600 m a.s.l. In the northern part of the region, rivers drain into the Atlantic Ocean. These rivers are short, with high slopes and high erosive power. The largest basins slightly exceed 1000 km^2 and 20 m^3 s^{-1} of mean daily flow, with highly variable valley widths that rarely exceed 1.5 km in most of the middle and upper courses. This area has a humid oceanic temperate climate (Rivas-Martínez et al., 2004) with an average annual temperature of 14 °C and an average annual precipitation of 1200 mm. The southern part of Cantabria is dominated by a continental climate with an average annual temperature of 10 °C and an average annual precipitation of 700 mm. In this part of the region, rivers belong to extensive and complex river systems which flow into the Mediterranean and the Atlantic, and they present more gentle relief and wider maximum valley widths than northern basins. In this area, rivers are generally long and with a gentle slope, draining into the Atlantic Ocean (Duero river basin) and into the Mediterranean Sea (Ebro river basin). The riparian vegetation is dominated by oceanic alder groves (*Alnus glutinosa*) in the Atlantic draining catchments from almost sea level up to 700 m and by submediterranean alder groves (*Alnus glutinosa*) in the southern draining catchments (Lara et al., 2004). Willow groves formed by *Salix atrocinerea* (Northern Cantabrian cordillera) and *S. cantabrica* (Southern Cantabrian cordillera) replace alder groves when they deteriorate, soils are not deep enough or there are large flow fluctuations. Higher in altitude, ashes (*F. excelsior*) or hazelnuts (*C. avellana*) might dominate riparian forest, while in steep valleys beech, oak and mixed Atlantic forest predominate. Finally, when riparian forests are impaired by human activities, the riparian vegetation is usually dominated by *Rubus sp.*, *Rosa sp.*, *Crataegus monogyna, Prunus spinosa* or even pasture formations. For a more detailed description of the study area see (Barquín et al., 2012)

2.2 Defining river network and river types

The geomorphological criteria used in this study requires a river network with the following geomorphological attributes: bankfull depth, channel and riverbank slope, valley floor width and riverbank geological hardness (considering as riverbank zone a buffer of 200 m from the river channel), as all these attributes are related with the flood height at a given location. This information is necessary to (i) classify the river network in morphological types and (ii) delimitate the riparian zone under the BFDAC approach. Thus, channel slope is important to distinguish among high-energy straight rivers and low-energy meandering rivers. Both riverbank slope and valley floor width characterise cross-section topography for each river reach. As valley floor width is difficult to define for some valley morphologies, we used valley width at a height of two times the bankfull depth as an approximation, based on its correspondence with the first terrace (Ilhardt et al., 2000). Finally, riverbank geological hardness was also included as it differentiates those locations where river flows across alluvial easily-erodible material from those flowing across hard difficult-erodible geological substrate.

The river network and its geomorphological attributes were derived using the analysis toolkit "NetMap" (http://www.netmaptools.org; Benda et al., 2007, 2009) following the procedure described by Benda et al. (2011). Hence, the network was delineated using flow directions inferred from a 5-m DEM, using the algorithms described by Clarke et al. (2008). In flat areas, DEMs usually contain cells that are completely surrounded by other cells at the same or higher elevation. These cells act as sinks to overland flow when deriving a river network using flow direction (Martz and Garbrecht, 1998). To solve this problem, we enforced drainage in low relief areas using GIS data on channel locations. Then the channel network was divided into a set of channel segments (500–1000 m) and split at confluences, as they are supposed to produce changes in channel and floodplain morphologies (Benda et al., 2004). This resulted in a set of stretches ranging from 3 to 850 m. Next, channel slope and riverbank slope were calculated at the endpoint of each segment from the DEM. Bankfull depth (BFD) was estimated using a regional regression of drainage area (A) and mean annual precipitation (P) to field measured depths over a range of channel sizes encompassing 195 river sites in the region of Cantabria (selected in areas with little to no engineered works). The results of this analysis yielded the following equation (Eq. 1):

$$\mathrm{BFD} = 0.63\,A^{0.1731}\,P^{0.1516} \tag{1}$$

Valley floor width was obtained from a DEM-derived raster. Each cell in this raster was associated with the closest river segment (in Euclidean distance) presenting the fewest and smallest intervening high points. Cell values showed the elevation difference (in terms of bankfull depth) among the cell and its associated channel. Using this raster, valley width at an elevation equivalent of two bankfull depths was assessed for each river segment. Riverbank geological hardness data source was the Spanish lithostratigraphic map (source: Geological and Mining Institute of Spain; spatial scale: 1:200 000). First we reclassified original geological classes into broader ones and then we assigned them a numerical value based on geological hardness (see Snelder et al., 2008). Finally, we obtained riverbank hardness for each river reach using NetMap tools.

Channel and riverbank slope, valley floor width and riverbank geological hardness were used to classify the river network in three geomorphological types by using PAM (partition around medoids) clustering in R software (R Development Core Team, 2008), previous data standardization.

2.3 Hydrological criterion and river network pruning

The area flooded by the 50-yr flood was available from a previous flood risk assessment study in the study area (IH Cantabria, 2008). In this study hydrological modelling with HEC_MHS (US Army Corps of Engineers, 2000) was used to derive flow data. This model required a high resolution DEM, a long series of precipitation data and information about land-use and soil type to quantify runoff and catchment response to precipitation. For each river basin, flow was calculated at several points that were representative of homogeneous sub-basins. On the other hand, river hydraulics modelling was performed using HEC-RAS (US Army Corps of Engineers, 2005) and HEC-Geo RAS module, which allows use of a DEM to derive required cross-section data. This model requires as input several parameters influencing flow behaviour: Manning's number, coefficients of expansion and contraction and boundary conditions.

As there is no human development in the upper reaches, the 50-yr flood was not available for headwaters (Strahler order 1 and 2). From the 427 km where this information was available, we discarded those river reaches presenting significant flood restrictions. We considered as significant restrictions all bank reinforcements or embankments longer than 100 m. We also excluded river reaches located downstream dams. The remaining river network comprised 321 km of rivers.

2.4 Surfaces derived from geomorphological criteria

GIS provides a fast technique to produce surfaces which are sensitive to stream bank topography. The main inputs to carry out this task are a DEM and a stream line. We used the DEM and streamline cited in Sect. 2.2 to apply two geomorphological approaches: the BFDAC and the path distance.

The bankfull discharge is the flow that fills a stream channel to the elevation of the active floodplain (Wolman and Leopold, 1957). The vertical distance from the deepest part of a channel to the bankfull elevation is called the bankfull depth. The area bordering a stream that will be covered by water at a flood stage of twice the maximum bankfull depth is called the floodprone area and corresponds on average to that which gets flooded by the 50-yr flood (Rosgen, 1996). However, floodprone height ranges from 1.3 times the bankfull depth in rivers of Rosgen's type E (low-gradient meandering rivers) to 2.7 times the bankfull depth in rivers of type A (highly-entrenched streams), and generally includes the active floodplain and the low terrace (Rosgen, 1996). Based on Rosgen's empirical data, valley width as considered in this study (valley width at a height of 2 times the bankfull depth) must coincide with the surface flooded by 50-yr flood. However, this relationship may be different when modelling in a GIS environment. To analyse this, we developed several surfaces calculated from different BFDAC heights and then we compared their adjustment with the 50-yr flood. These surfaces were obtained following the same procedure described for the valley floor surface in Sect. 2.2 and using different bankfull depth heights ranging from 0.25 to 3 using steps of 0.25.

The path distance is a surface of values indicating the relative costs of moving from the stream cells up into the stream valley, accounting for slope and elevation change. It only requires a stream line and a DEM to be assessed. Path distance surface (raster format) was derived using the path distance tool in ArcGis software (ESRI, 2011), producing surfaces with a threshold value that range from 50 to 350 using steps of 50.

This has been done by reclassifying path distance raster using the above-mentioned threshold values and converting raster into polygon (shapefile).

Therefore, several surfaces (in ArcGIS polygon shapefile format) were derived for each geomorphological approach (Fig. 3). Hereafter we will refer to them as geomorphological surfaces. Those derived following the BFDAC are cited in the text as BFD × X, being X the factor multiplying bankfull depth (e.g. BFD × 1.25). On the other hand, geomorphological surfaces derived using the path distance approach are cited as PD-Y, being Y the threshold value used to generate that surface (e.g. PD-250).

2.5 Data analyses

Each geomorphological surface was fragmented based on river type using ArcGis software (ESRI, 2011) and the total area in each type was calculated. To evaluate the adjustment of each surface with respect to the 50-yr flood we have used two different methods:

(i) Minimum exceeding score (Eq. 2). This method combines the two possible exceeding surfaces: geomorphological surface exceeding area (GSEA) and 50-yr flood exceeding area (T50EA; Fig. 4). GSEA is the area of the geomorphological surface exceeding the 50-yr flood, while the T50EA is the area of the 50-yr flood not covered by the geomorphological surface. This latter parameter results from subtracting the coinciding area (CA; Fig.4) from the 50-yr flood. The optimal geomorphological surface is that achieving the lowest minimum exceeding score.

$$\text{Minimum exceeding score} = \frac{\text{T50EA} + \text{GSEA}}{100} \quad (2)$$

(ii) Total area (Eq. 3). This method does not look at coinciding or exceeding areas, but only considers the deviance between the value of the area occupied by the geomorphological surface and the value of the area covered by the 50-yr flood.

Total area optimum value is 100, and values above or below are considered as deviations. This condition may not reflect an "optimum adjustment", but as all geomorphological surfaces and the 50-yr flood are supposed to be sensitive to geomorphology, we have considered exploring this possibility.

$$\text{Total area} = \frac{\text{geomorphological surface total area}}{\text{area covered by the 50-yr flood}} \times 100 \qquad (3)$$

3 Results

Cluster analysis resulted in three well defined groups (Fig. 2). The first of them included 1782 cases and corresponded with open valleys, as it presented the widest valleys (average > 200 m), the lowest geological hardness and the lowest channel and stream bank (average of 6 degrees and 13 %, respectively) slopes. The second one encompassed 1953 cases and corresponded with shallow-vee valleys presenting intermediate characteristics between groups 1 and 3. Finally, the third group included 1908 cases and corresponded with deep-vee valleys and gorges, as it showed narrower valley widths (average < 50 m), high geological hardness and the steepest channel and stream bank slopes (average of 22 degrees and 50 %, , respectively).

All geomorphological surfaces were sensitive to valley morphology, being narrower in constrained valleys due to closer and steeper slopes (Fig. 3). By incrementing the factor multiplying bankfull depth or the path distance threshold value, geomorphological surfaces became wider and filled those gaps that lower threshold values can not fill (corresponding with low hills located in the valley bottom). The path distance approach produced wider surfaces than BFDAC in unconstrained valleys, while the opposite trend was found in constrained valleys.

The adjustment between geomorphological and hydrological criteria, in terms of coinciding and exceeding areas (Fig. 4), showed the same general trend for all river types and the two geomorphological criteria (Fig. 5). As it was expected, increasing the geomorphological surface (by increasing the factor multiplying bankfull depth or increasing the path distance threshold value) increased CA, and therefore decreased T50EA. However, increasing the geomorphological surface also increased GSEA. Besides, the rate of increase of GSEA was greater than that of CA, except in deep-vee valleys, where they presented almost the same rate. Intersection between the T50EA and the GSEA graphically indicates the minimum exceeding score optimal geomorphological surface. This intersection occurred at larger geomorphological surfaces when moving from open valleys to more entrenched ones, although there are no differences between open and shallow vee valleys when using the BFDAC approach. Despite the homogeneity in the above cited trends, the BFDAC reaches higher CA values than path distance. Consequently, path distance reaches higher T50EA values than BFDAC. However, both approaches show similar values for GSEA.

Both minimum exceeding score and total area indicated the same or close optimal geomorphological surfaces (Fig. 6) for each valley type. When using minimum exceeding score, all the considered geomorphological surfaces produced values closer to the optimum in deep vee valleys (which is reflected by 4 different geomorphological surfaces for BFDAC and by 2 surfaces for path distance). However, in open valleys increasing geomorphological surface causes rapid deviation from the optimum value, while shallow vee valleys presented intermediate pattern between open and deep vee valleys. The total area method showed a positive linear relationship between the value defining the geomorphological surface and its total area. The slope of this relationship became steeper when moving from deep vee to open valleys. The BFDAC that best matched the 50-yr flood was BFD × 0.5 in open and shallow vee valleys, while in deep vee valleys it was around BFD × 1.25. When using path distance, optimal geomorphological surfaces were close to PD-100 in open and shallow vee valleys and around PD-300 in deep vee valleys.

4 Discussion and conclusion

Our aim of easily obtaining a 50-yr-flood-matching riparian zone by using geomorphological criteria was fully achieved by merging the optimal geomorphological surface for each valley type. Calibration was needed to provide the boundaries of geomorphological surfaces with hydrological meaning, because GIS-derived thresholds can differ from those established by empirical studies. Our calibration framework took into account the influence of the following parameters: geomorphological criterion, valley type and adjustment assessment method. All of these parameters are discussed below. However, attention should be paid when using DEMs with a spatial resolution different from that used in this study, as thresholds are suggested to be also dependant on this parameter (Sutula et al., 2006; Abood and Maclean, 2011).

Regarding geomorphological criteria performance, BFDAC and path distance seem two be valid approaches to delineate riparian areas, both presenting the advantage of being sensitive to floodplain morphology. Optimal geomorphological surfaces for BFDAC correspond with slightly higher CA (5–16 % depending on valley type) and slightly lower GSEA (0–20 %) and T50EA (5–16 %) than those for path distance. This is an advantage of BFDAC approach. However, path distance does not require bankfull depth values for each river reach in the network and it can be rapidly calculated in GIS. Therefore, the choice of the proper geomorphological criterion depends on the resources and accuracy required in the study. Besides, both BFDAC and path distance present the advantage that can be used to account for the gradients present in riparian zones by assigning membership scores to each band defined by a different threshold value (the lesser is the threshold value, the higher must be the membership score as the river influence is also higher).

Despite of differing in characteristics as streamside slope or valley width, there is no necessity of distinguishing between open valleys and shallow vee valleys (as defined in this study) when using geomorphological criteria to delineate riparian areas, as the same optimal geomorphological surface is obtained for both valley types. However, it is necessary to use a different geomorphological surface for deep vee valleys and gorges because they require wider surfaces than unconstrained valleys to match with the 50-yr flood, as described by Rosgen (1996). Moreover, the worst adjustment between hydrological and morphological surfaces, showed by maximum combinations of the two exceeding surfaces (T50EA and GSEA), occurred in open valleys. The same result was obtained by Sutula et al. (2006). This may be due to the fact that unconstrained valleys present more complex fluvial landscapes than constrained ones. We have also considered that tributary confluences may also partly explain the disarrangement between geomorphological surfaces and the 50-yr flood, as in general terms they result in lower channel gradients and wider channel and floodplains (Benda et al., 2004; Fig. 7a) and they have not been considered in defining river types. However, within the study area we found many examples of confluences of the main channel with large tributaries where confluence effects are much less determinant of floodplain width than topographic constrains such as steep riverbank slopes or hardly-erodible riverbank materials (e.g., Fig. 7b, where the main channel is the Deva River and Quiviesa and Bullón are large tributaries). Hence, it does not seem appropriate to include a variable accounting for confluence effects when classifying valley type, at least in mountainous study areas such as the one included in here. In addition, we do find larger fluvial landscapes immediately above and below valley constrictions (Fig. 7c), as commented in Benda et al. (2001).

The two methods used to select the optimal geomorphological surfaces provided almost the same result, despite the fact that total area is more subjective than minimum exceeding score. Both approaches can therefore be used to determine the geomorphological surface that best matches the 50-yr flood, or to evaluate the adjustment between any other two surfaces. Attention should however, be paid when using the minimum exceeding score in deep vee valleys. This method could suggest that any geomorphological surface is valid in these valleys, as the scores they produce with the different surfaces are all close to the optimum. By looking at total area it can be seen that this is not true, as moving backward or forward the optimum value significantly causes rapid deviation from 100 % of total area, and this is reflected in exceeding and coinciding area combinations away from the optimum.

In conclusion, our results suggest that using GIS to delineate sensitive-to-geomorphology hydrologically-meaningful riparian zones is feasible and relatively easy and fast. This task does however, require local calibration in order to find an optimal threshold value for the geomorphological criterion which maximizes the coinciding and minimizes the exceeding with respect to the hydrological surface. Our results also confirmed that this optimal value is valley-type dependent, as deep vee valleys and gorges require higher threshold values than shallow vee and open valleys.

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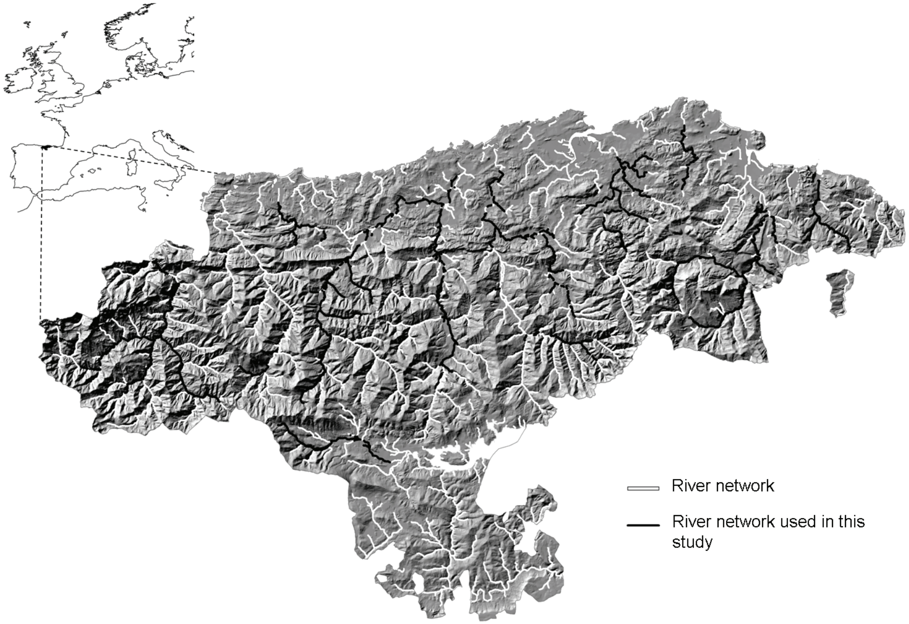

Fig. 1. River network of the Cantabrian region, Northern Spain. White river lines cover the extent of the whole Cantabrian river network and black lines the river network used in this study.

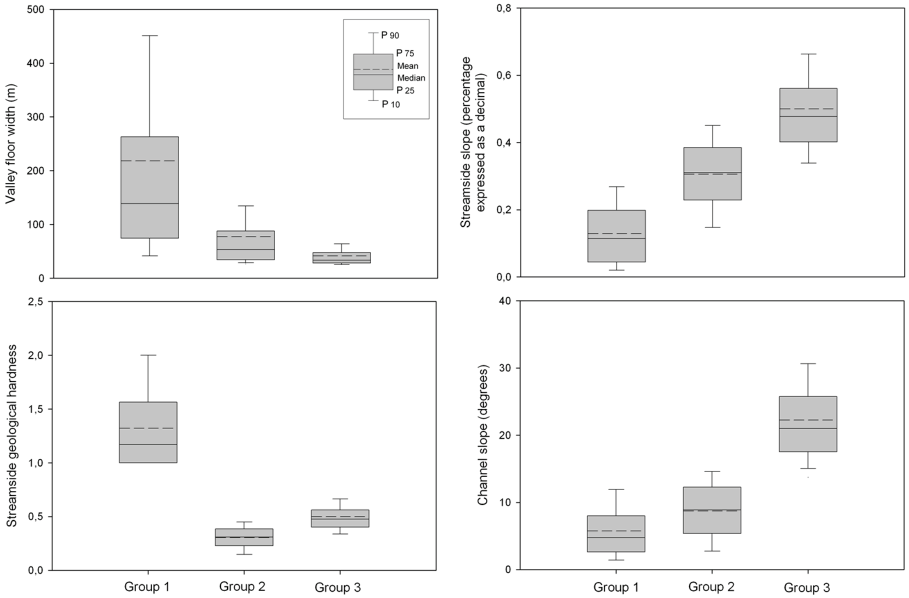

Fig. 2. Boxplots of the four variables involved in the river reach classification for the three geomorphological valley types.

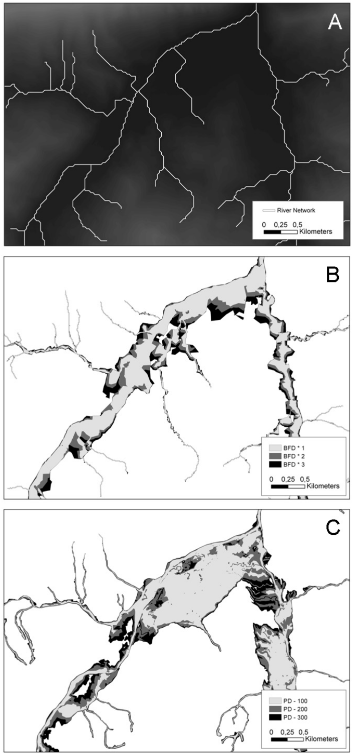

Fig. 3. Illustration of river centre-lines over the digital elevation model at a confluence **(a)** and how BFDAC geomorphological surfaces (**b**; at 1, 2 and 3 bankfull depth heights) and path distance geomorphological surfaces (**c**; at 100, 200 and 300 threshold values) were derived.

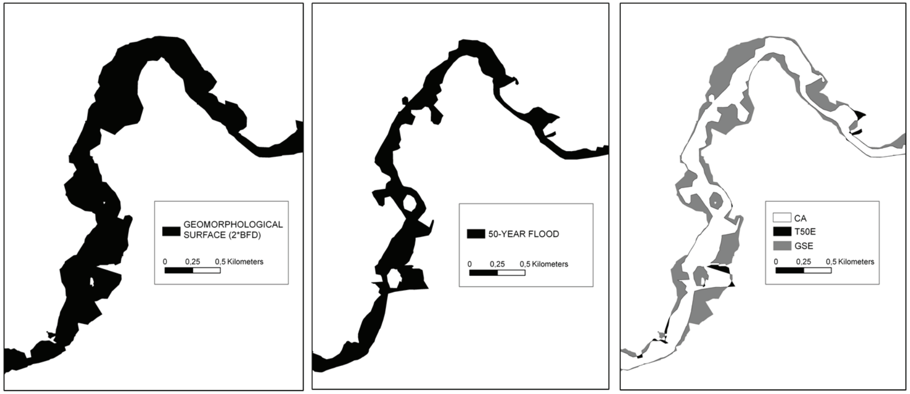

Fig. 4. Delineation of coinciding area (CA), 50-yr flood exceeding area (T50EA) and geomorphological surface exceeding area (GSEA) to evaluate the adjustment between geomorphological (2 × BFD) and hydrological criteria (50-yr flood) derived surfaces.

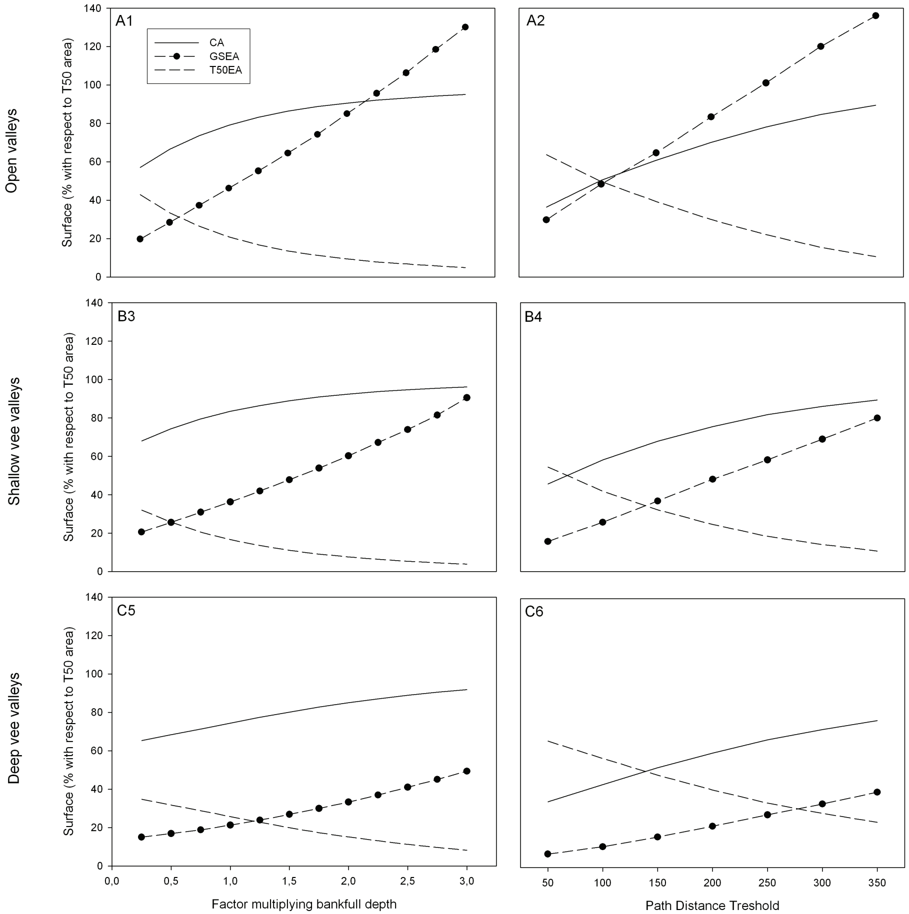

Fig. 5. Coinciding area (CA), 50-yr flood exceeding area (T50EA) and geomorphological surface exceeding area (GSEA) for BFDAC (1, 3 and 5) and path distance (2, 4 and 6) geomorphological surfaces for open valleys **(a)**, shallow vee valleys **(b)** and deep vee valleys **(c)**.

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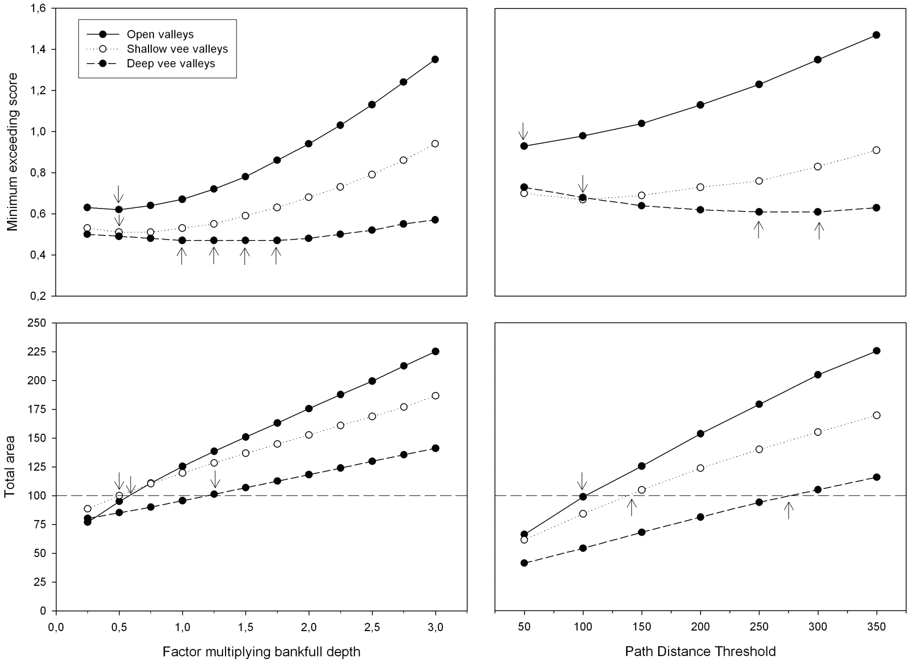

Fig. 6. Values obtained for the two different methods used to evaluate the adjustment between geomorphological surfaces and the 50-yr flood. Arrows indicate optimal threshold values (best adjustment) for each geomorphological approach and valley type.

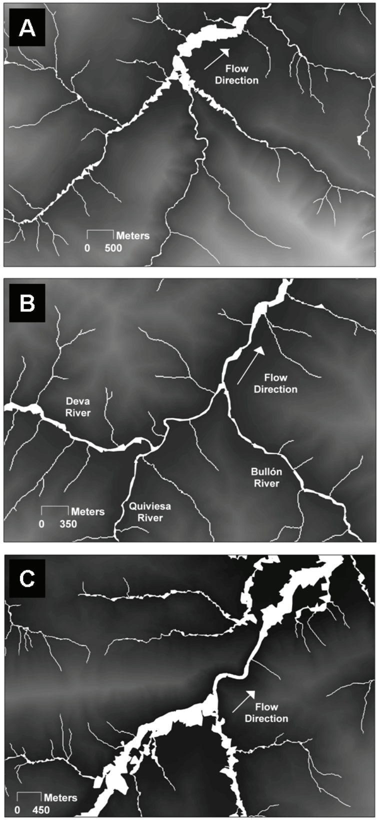

Fig. 7. Illustration of the floodprone area at 1.25 × BFD over the digital elevation model: at a river confluence deriving in wider floodprone areas **(a)**, at a river confluence not deriving in wider floodprone areas **(b)** and at an unconstrained-constrained-unconstrained valley transition **(c)**.

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