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FLUVIAL TOPOGRAPHIC ZONE CONCEPT

EL CONCEPTO DE ZONA TOPOGRÁFICA FLUVIAL

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Abstract

The objectives of the present study were: (i) to propose a new concept of a zone where the relationship between the river and hillslopes is more intense, which is called Fluvial Topographic Zone (FTZ), as well as to describe the method to delineate this zone on maps; and (ii) to compare the Permanent Protection Area (PPA) with the FTZ along the main river (28.8 km) of Bugres river basin (78.2 km^2) which is located in Rio Negrinho city, Santa Catarina state, Brazil. The indices *TI* (Topographic Index), *STI* (Soil Topographic Index), and sinuosity were selected to verify the applicability of FTZ, because *TI* and *STI* are mainly influenced by the hillslopes, meanwhile sinuosity is related to the river. A significant correlation may indicate that such zone comprises a more intense interaction between the river and hillslope. The boundary of FTZ is the nearest contour line to the river channel. This procedure was evaluated for the studied main river by using a map (1:50,000). *TI*, *STI*, and the sinuosity of the main river and of the contributing areas were estimated. Subsequently, the correlations of the sinuosity with these two indices were evaluated for the whole basin and considering only the FTZ. It was showed that the sinuosity is more strongly influenced by the topography than by the soil properties and that this influence becomes more significant in FTZ. It implies the importance of FTZ as an area for protection as well as for scientific researches. Based on the Brazilian law, the PPA was delimited along the main river and its area was compared with FTZ. The FTZ and PPA comprise 10% and 3% of the total basin area, respectively. This comparison shows that only in the upper part of the main river the FTZ coincides with the PPA very well and that it gradually increases towards downstream. In the lower part of the basin, the width of FTZ reaches 300 m, while PPA keeps the 30-m width. The obtained results permit to conclude that FTZ comprises river meandering dynamics, which is of extreme importance for the preservation of various species of both flora and fauna of the riparian zone. Furthermore, the variable width of FTZ depending on each river can be considered positive, because it is adaptable to rivers' peculiarities.

Keywords: Hydrogeomorphology, Permanent Preservation Area, Riparian zone, sinuosity, Topographic index, Fluvial Topographic Zone.

Resumen

Los objetivos del presente estudio son: (i) proponer un concepto nuevo de una zona, la Zona Topográfica Fluvial (FTZ), donde la relación entre río y vertiente sea más intensa, así como describir el método para delimitar esta zona en mapas; (ii) comparar el Área de Preservación Permanente (PPA) con la FTZ a lo largo del río principal (28,8 km) de la cuenca dos Bugres (78,2 km^2) que se ubica en la ciudad de Rio Negrinho, en el departamento de Santa Catarina, Brasil. Los índices *TI* (Índice Topográfico), *STI* (Índice Topográfico de Suelo), y sinuosidad fueron seleccionados para verificar la aplicabilidad de la FTZ, considerando que *TI* y *STI* son influenciados principalmente por las vertientes, mientras la sinuosidad está relacionada esencialmente al río. Por lo tanto, una correlación significativa de ellos debe indicar que la relación río-ladera es más intensa en esta zona. La curva de nivel más cercana al canal del río es el límite de la FTZ. El procedimiento de trazado de FTZ fue realizado para el río dos Bugres utilizando un mapa topográfico (1:50.000). *TI*, *STI* y la sinuosidad de las áreas de contribución fueron estimadas. En seguida las correlaciones de la sinuosidad con los dos índices fueron evaluadas considerando el área de toda la cuenca y sólo el correspondiente a FTZ. Los resultados revelan que la sinuosidad es más fuertemente influenciada por la topografía do que por las propiedades del suelo, y esta influencia se revela más significativa en la FTZ. Esto implica la importancia de la FTZ como área de preservación, así como en investigaciones científicas. Con base en la legislación nacional de Brasil, la PPA del río dos Bugres fue delimitada y comparada a FTZ. FTZ y PPA consisten en 10% y 3% del área de la cuenca, respectivamente. FTZ coincide totalmente con PPA sólo en la parte alta del río principal, y aumenta gradualmente aguas abajo. En la parte baja de la cuenca FTZ alcanza la anchura de 300 m, mientras PPA mantiene siempre el ancho de 30 m. Por lo tanto, los resultados permiten concluir que FTZ comprende la dinámica de meandramiento fluvial, la cual es de extrema importancia para la preservación de diversas especies de flora y fauna en la zona riparia. Además, el facto del ancho de la FTZ ser variable de acuerdo con cada río debe ser considerado muy positivo, porque se adapta a las peculiaridades de cada río.

Palabras Clave: Hidrogeomorfologia, Área de Preservación Permanente, Zona Riparia, Sinuosidad, Índice Topográfico, Zona Topográfica fluvial.

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INTRODUCTION

Riparian zones, wetlands, and hyporheic zones can be considered as ecotones, which were defined by Holland (1988) as transitional zones between adjacent ecological systems of several types and spatial scales. Kolasa & Zalewski (1995) emphasize the potential role that such ecotones play in maintaining and shaping of various ecological processes. In this sense the results obtained by Smith et al. (1997) suggest that ecotones may be integral to the production and maintenance of biodiversity in tropical rainforests. Poole (2010) defined the fluvial hydrogeomorphology with the question: “How are streams (channels, riparian zone/floodplains, and alluvial aquifers) shaped by surface and subsurface water dynamics and how does the resulting shape influence spatial and temporal patterns of surface and subsurface water movement?”. Therefore, hydrogeomorphological processes result from the action of water originating from both river and hillslope. Then, they influence variables such as humidity, temperature, sedimentation rate, and consequently the ecological ones. Ecotones often intensify many of these processes (Kolasa & Zalewski, 1995), which are important for environmental preservation.

The fluvial channel patterns (straight, meandering, braided, etc.) and the dynamic modification of riverbanks can be described by means of sinuosity. This index is scientifically related to morphological, sedimentological and hydraulic characteristics of a river (Ratzlaff, 1991). Given that the erodibility of the riverbanks is associated to their grain size (Knighton, 1998), Schumm (1963) showed that sinuous streams are characterized by a high percentage of silt-clay in the perimeter of the channel.

Geology, land use and topography are factors that directly influence on the hydrological response of the catchments (Kirkby et al., 2002). According to Dunne (1978), the topography of the basin is a variable that strongly influences on the movement of both groundwater and surface water.

For representing the distributed topographic characteristics of a basin, Beven & Kirkby (1979) proposed the Topographic Index – *TI* which is a hydrogeomorphic parameter showing areas with potential for surface runoff generation by saturation. This index was initially tested in TOPMODEL (Topographic-based hydrological model). Furthermore, in order to spatialize soil heterogeneous characteristics and better predict the behavior of infiltration into the soil, Beven (1986) proposed the Soil Topographic Index - *STI* and implemented it in TOPMODEL. The difference between *TI* and *STI* is that the latter includes soil transmissivity.

The variables (sinuosity and topographic indices) explored in the present work to reveal other basin information are obtained from maps. That is one of the advantages of applying this analysis, because as Tarolli (2014) highlighted, in the last decade, a range of new remote-sensing techniques has led to a significant increase in terrain information, providing new opportunities for a better understanding of earth surface processes based on geomorphic signatures.

Given the importance of the ecotones, there are some specific laws for environmental protection that aim to preserve them. In Brazil, because of such a law, Forest Code, to protect riparian zones, there are the so-called permanent preservation areas (PPA) along the riversides. This protection is strongly justified by their several functions such as river sediment control, mitigation of river water temperature amplitude, and so on. Based on this law, the PPA width varies from 30 m to 500 m depending on river width. However, there is still much uncertainty on what should be its appropriate width along the river.

Therefore, the objectives of the present study were: (i) to propose a new concept of a zone where the relationship between the river and hillslopes is more intense, which is called Fluvial Topographic Zone (FTZ), as well as to describe the method to delineate this zone on maps; and (ii) to compare the PPA with the FTZ on the main river (28.8 km) of Bugres river basin which is located in Rio Negrinho city, Santa Catarina state, southern Brazil. Here, the scientific interest was to verify if some characteristics of river and hillslope in this zone are different from those in the whole basin. In the present study, the river and hillslope characteristics are represented with sinuosity and topographic indexes, respectively.

MATERIALS AND METHODS

Study area

The Bugres river basin – BRB (78.2 km^2) is totally inserted in the Rio Negrinho city, Santa Catarina state, Brazil. By observing the digital elevation model (DEM) it is noted that the altimetry strongly varies near the headwater, and that the main thalweg is incised except on the reach very near to the basin outlet (Fig. 1). Its land use is mostly characterized by native forest (Mixed Ombrophilous Forest), secondly pine reforestation, and lastly agriculture.

The predominant soils of BRB are mineral soils, not hydromorphic with an incipient subsuperficial horizon quite heterogeneous in terms of color, thickness, texture, and chemical activity of the clay fraction, i.e. they are similar to Inceptisols. Furthermore, these soils are originated from materials related to rock composition of quite variable nature, such as the rocks that constitute the metamorphic rocks of Brusque Complex, Eo-Paleozoic granite, Paleozoic sedimentary rocks (Botucatu sandstone), and effusive rocks of Serra Geral Formation (EMBRAPA, 1998).

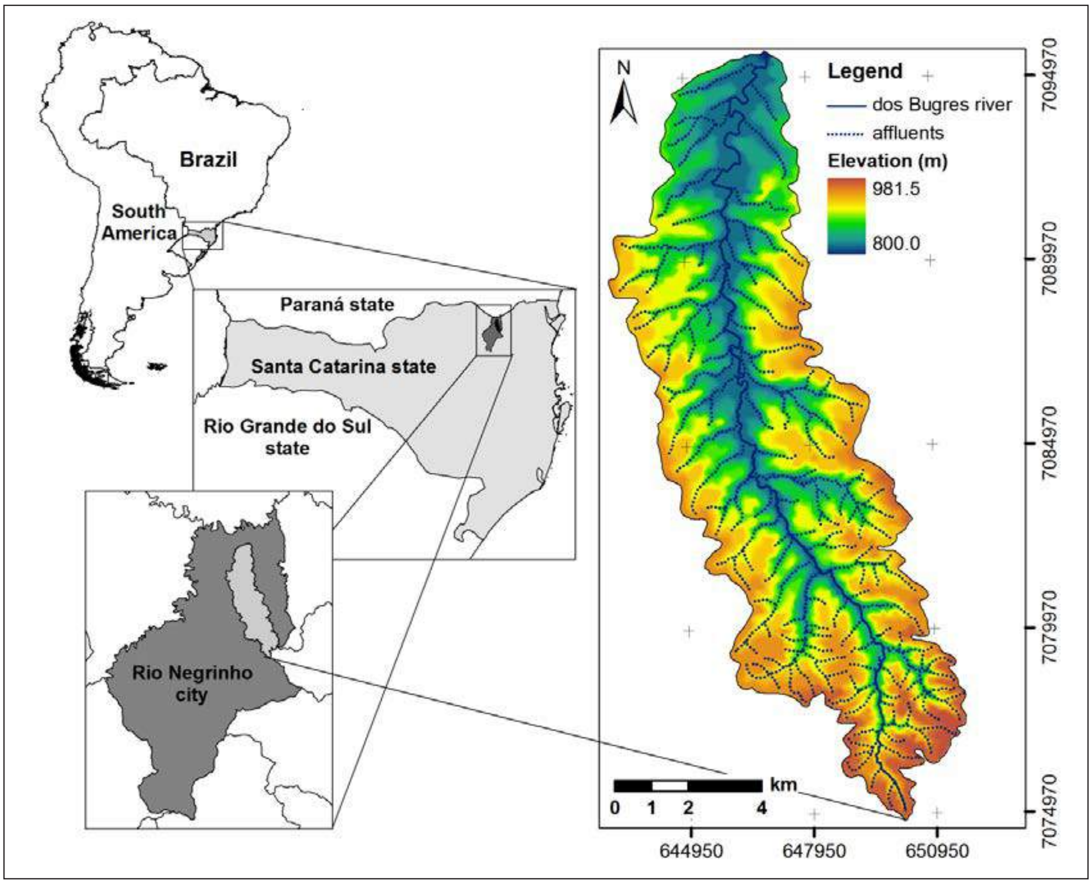

Figure 1. Localization and DEM of Bugres river basin

Materials

The digital topographic map (1:50,000) were interpolated to generate the DEM with 30-m resolution. The results of Sørensen & Seibert (2007), as well as several studies, revealed considerable differences between topographic indices computed for DEMs of different grid resolution. Vaze et al. (2010) noted that the accuracy and resolution of the input DEM have serious implications on the values of the hydrologically-important spatial indices derived from the DEM, and recommended to use the higher resolution DEM available. In this sense, we adopted the highest spatial resolution by considering the scale of the available maps (altimetry, drainage network, and soil survey), i.e., 30 m.

Basin subdivision

The BRB was subdivided into 20 drainage areas from the headwater to the outlet (Fig. 2). The subdivision was based on the following criterion: the outlet of each drainage area is located where a 2nd-order river joins the main Bugres river, and its delineation is made according to the relief.

For example, the area A1 begins at the top and ends where there is a junction of a 2nd-order river and the main river. Then, the area A2 begins just after area A1, and the procedure of subdivision continues until the BRB outlet. These areas support the analysis of the variables´ behavior along the BRB.

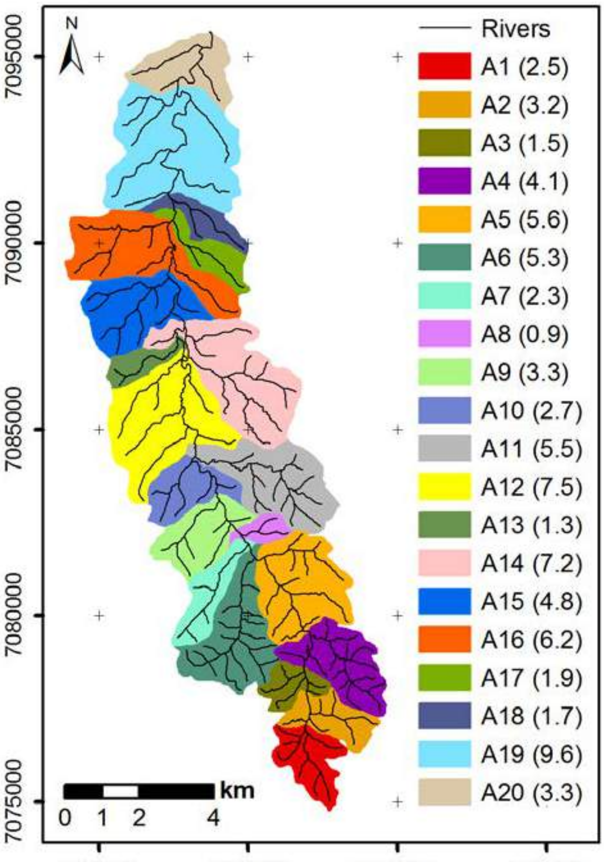

Figure 2. Delineation of drainage areas (in parenthesis their respective areas in km^2)

Spatial distribution of soil properties

The estimation of *STI* requires spatially-distributed data of soil depth (*D*) and saturated hydraulic conductivity (*Ks*). Firstly we elaborated a BRB map of soil classification (scale 1:250,000) based on a soil survey conducted in 2004 by the Centre for Information on Environmental Resources and Hydrometeorology of Santa Catarina state (EPAGRI/CIRAM, 2008) (Fig. 3). In this survey, some physical properties of each soil type, the number of layers (or horizons), and its range of depth are also available (Tab. 1).

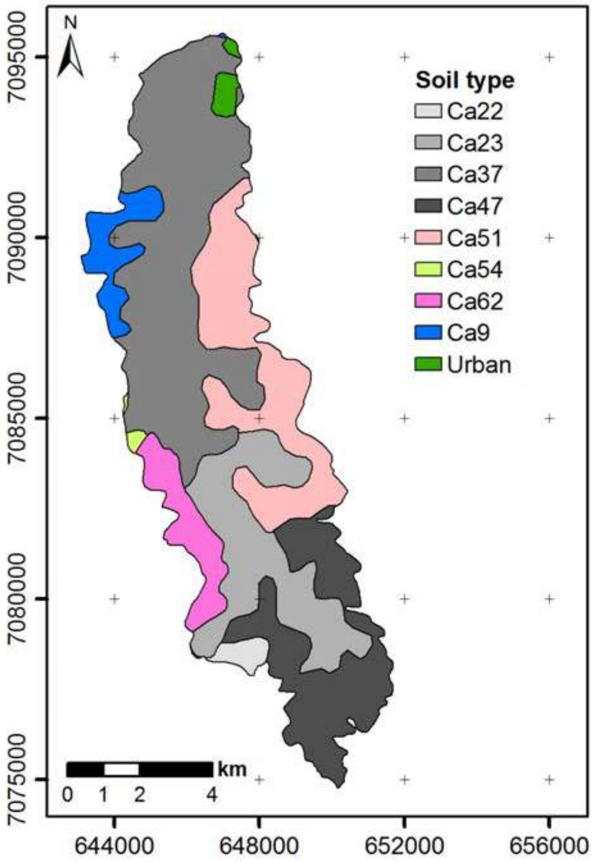

Figure 3. Soil types in BHRB

Table 1. Range of variation of the depth of each soil type present in BHRB

Soil Type	Horizon depth (cm)	
	1	2
Ca22, Ca23, Ca54	60 - 150	60 - 150
Ca51, Ca62	60 - 150	< 60
Ca37, Ca47, Ca9	60 - 150	-

After preparing the soil classification map and checking the range of its respective depth, the spatial distribution of soil depths in BRB was verified. For it, we applied the equation proposed by Saulnier et al. (1997), i.e.

$$D_i = D_{\max} - \left(\frac{D_{\max} - D_{\min}}{z_{\max} - z_{\min}} \right) \cdot \left(z_i - z_{\min} \right) \tag{1}$$

where D_i is the soil depth at pixel (m); D_{max} and D_{min} are the maximum and minimum soil depth encountered in the basin, respectively (m), z_i is the elevation at pixel (m); z_{min} and z_{max} are the minimum and maximum elevation found in the basin, respectively (m). In this equation, the values of D_{max} and D_{min} used were 3.0 and 0.6 m, respectively, they were obtained by verifying the number of layers and their depth range for each soil type shown in Table 1.

The *Ks* value was estimated by applying the computer program Rosetta Lite Version 1.1 proposed by Schaap et al. (2001). The program is included in the model HYDRUS-1D and implements 5 hierarchical pedotransfer functions to estimate soil water retention parameters and saturated hydraulic conductivity.

Although the input data in this program can be textural classes only, texture (percentage of sand, silt and clay), bulk density, and one or two water retention points, the present study used only the textural class data obtained in the soil survey (EPAGRI/CIRAM, 2008) to estimate the *Ks* mean value for each soil type. These values were interpolated by the nearest neighbor method to generate a spatially-distributed *Ks* map of BRB.

Table 2. Estimative of Ks by applying Rosetta Lite Version 1.1

Texture*	Textural Class **	*Ks* (m/day)
Medium	Silt	0.4374
Clayey	Clay	0.1475
Very clayey	Clay loam	0.0818

*Soil survey (EPAGRI/CIRAM, 2008).

**Input data on *Rosetta Lite Version* 1.1.

Calculation of Topographic Index (*TI*) and Soil Topographic Index (*STI*)

TI and *STI* were computed in ArcGIS 9.3.1 by applying eq. 2 and 3 respectively.

$$TI = \ln\left(\frac{a}{\tan \beta} \right) \tag{2}$$

where $a = (A/c)$ is the area per unit contour; *A* is the drainage area to the section considered (m²); *c* is the contour length of the portion of the area considered (m); and β is the slope of the plot area (degrees).

$$STI = \ln\left(\frac{a}{\tan \beta \times T_0} \right) \tag{3}$$

where T_0 (= *Ks·D*) is the transmissivity (m²/day); *Ks* is the saturated hydraulic conductivity (m/day); and *D* is the soil depth (m). The calculation procedure is shown in Figure 4. These values were calculated for the entire basin.

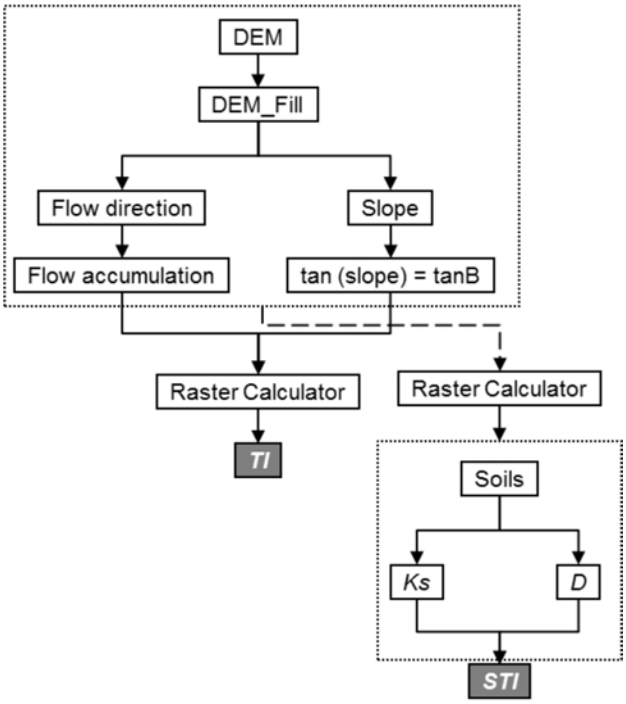

Figure 4. Calculation scheme of *TI* and *STI* using ArcGIS

According to Wood et al. (1988), *TI* is a fundamental parameter in TOPMODEL and is used to predict the topographic redistribution of subsurface moisture. Therefore, the *TI* map reveals potential areas to generate saturation surface (or subsurface) excess runoff. On the *STI* map, areas with higher values are also identified as contribution areas to runoff.

Calculation of sinuosity

The sinuosity was analyzed only on the main river of BRB. The sinuosity of a stream is defined as the ratio of the curvilinear length along the river (C_{RP}) and the straight line distance (C_T) between the end points defined on the stream (Fig. 5). This parameter was calculated for each reach delimited by the drainage areas of the studied basin(Fig. 2).

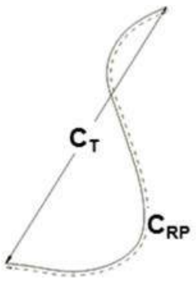

Figure 5. Schematic representation of the measurements involved in the sinuosity calculation

Delineation of the Fluvial Topographic Zone (FTZ)

The FTZ is superficially delimited by the nearest contour line to the river channel. Its delineation consists of the following steps (Fig. 6): (1) to get a topographic map which includes the basin of interest, its main river (or any river channel whose FTZ is interested to be delineated), and contour lines; (2) to identify the nearest contour line to the river of interest; (3) to join the contours where the nearest contour line changes to other one.

There is an agreement that spatial and temporal scale influences the analysis of environmental processes. In the case of the present work, we are searching for a zone where the interaction between fluvial and hillslope processes is more intense. The scale of the maps available to verify the applicability of FTZ was 1:50,000, and the influence of the maps' scale on the FTZ delineation was not yet explored. Therefore, it is necessary to test it with other scales.

After delineating the FTZ, the relations between *TI* and sinuosity and between *STI* and sinuosity were analyzed for the whole basin and only for the FTZ.

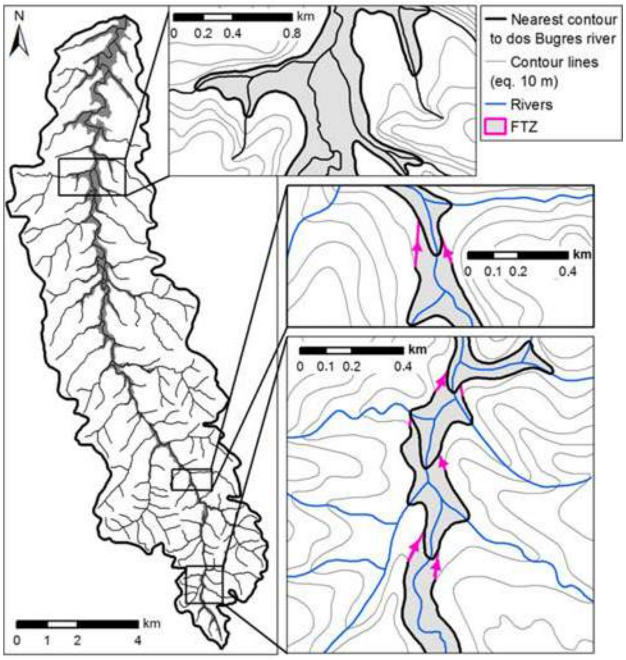

Figure 6. Delineation of Fluvial Topographic Zone

There are other studies that proposed concepts and methods to delimit an area along the river channel for various objectives. For example, Schreiber & Demuth (1997) defined "*river network areas*" and proposed a new methodology for regionalization of low flows. Though their idea is very similar to that of the present study to delimit the FTZ, they applied a different criterion of delineation: the areas were defined as corridors with 1 km width and length along the main river.

As well as Schreiber & Demuth (1997), the purpose of determining such areas is to identify a more homogeneous zone in the basin. In case of the present study, this zone, i.e. FTZ is where hillslopes relate more directly to the main river.

RESULTS AND DISCUSSION

Figure 7 shows the spatial distributions of *D* and *Ks* in BRB. The highest values of *Ks* are found in the low portion of the basin, close to the basin outlet. It can be mainly explained by the fact that the soil texture in this area is predominantly sandy. Soil depth has a direct relationship to the altimetry. This general aspect is observed in Figure 7b.

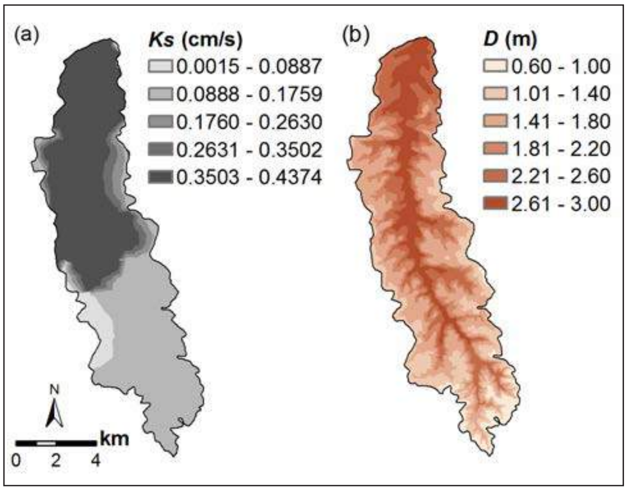

Figure 7. Spatial distribution of soil properties in BRB. (a) *Ks*; and (b) *D*

Some of the most important maps elaborated in the intermediate stages of *TI* and *STI* calculation are in Figure 8. On the map of flow direction (Fig. 8a) an integer value is assigned for each cell according to its flow direction. It is noted that the flow direction is consistent with the topography and hypsometry of the basin.

On the map of Flow accumulation (Fig. 8b), the value assigned to each the cell is correspondent to the quantity of cells that directed to it. Thus, the highest values of flow accumulation are found on the main river. Also, the maps of slope (β) and tangent of slope (tg β) are shown in Fig. 8c and Fig. 8d, respectively.

The procedure presented in Figure 6 was applied only to the main river of the BRB. The FTZ delineation for the BRB has been already shown in the same figure. In general, the FTZ width varies and increases from the headwater to the outlet. In Figures 9a and 9b, it is observed that the interval of values of *TI* and *STI* are almost the same, with a difference that the STI's interval is smaller. However, no significant difference about the indication of potential areas to generate saturation excess runoff is noted on the maps. It is also observed that the mean *TI* increases when the mean slope decreases. Moreover, the largest values of *TI* and *STI* are encountered at those cells associated to channel network and the smallest at cells located at the top of the hillslope. The maps of *TI* and *STI* in FTZ are presented in Figures 9c and 9d.

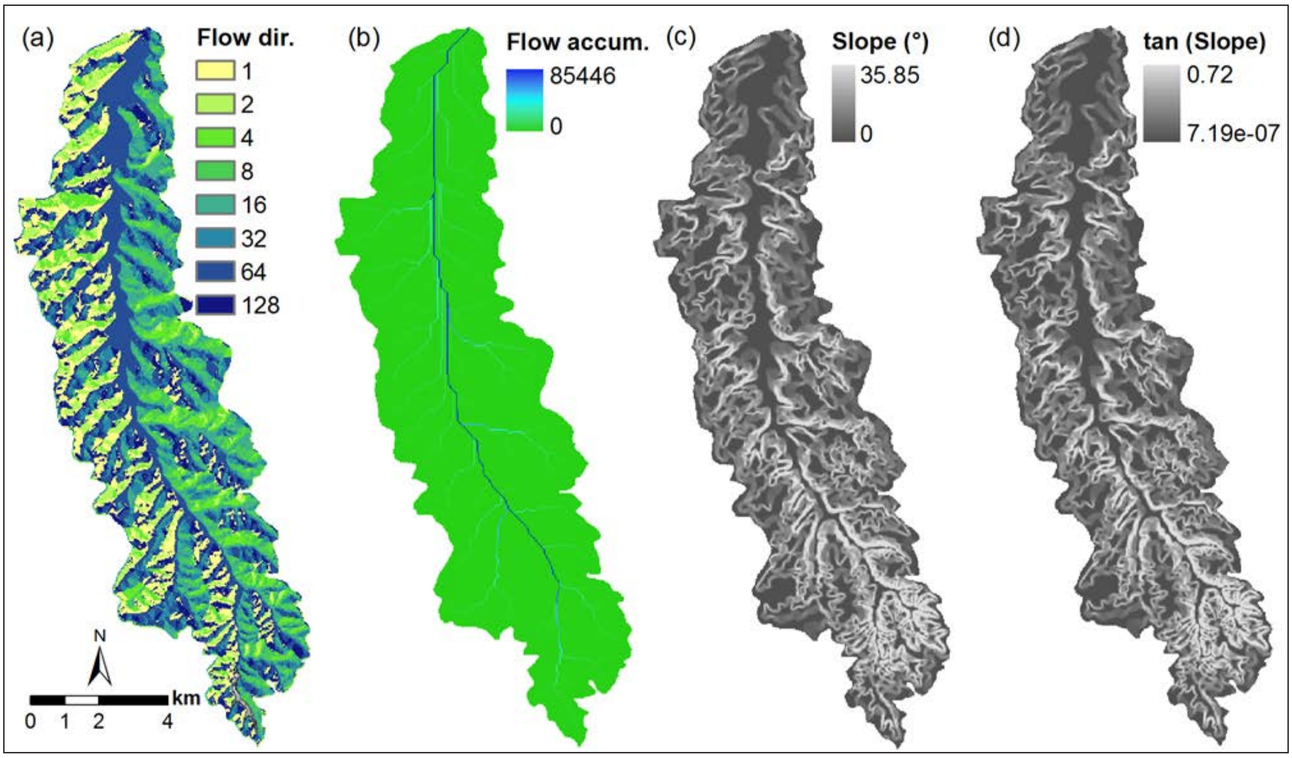

Figure 8. Intermediary steps of calculation of TI and STI. (a) Flow direction; (b) Flow accumulation; (c) Slope (β); and (d) Tangent of slope (tanβ)

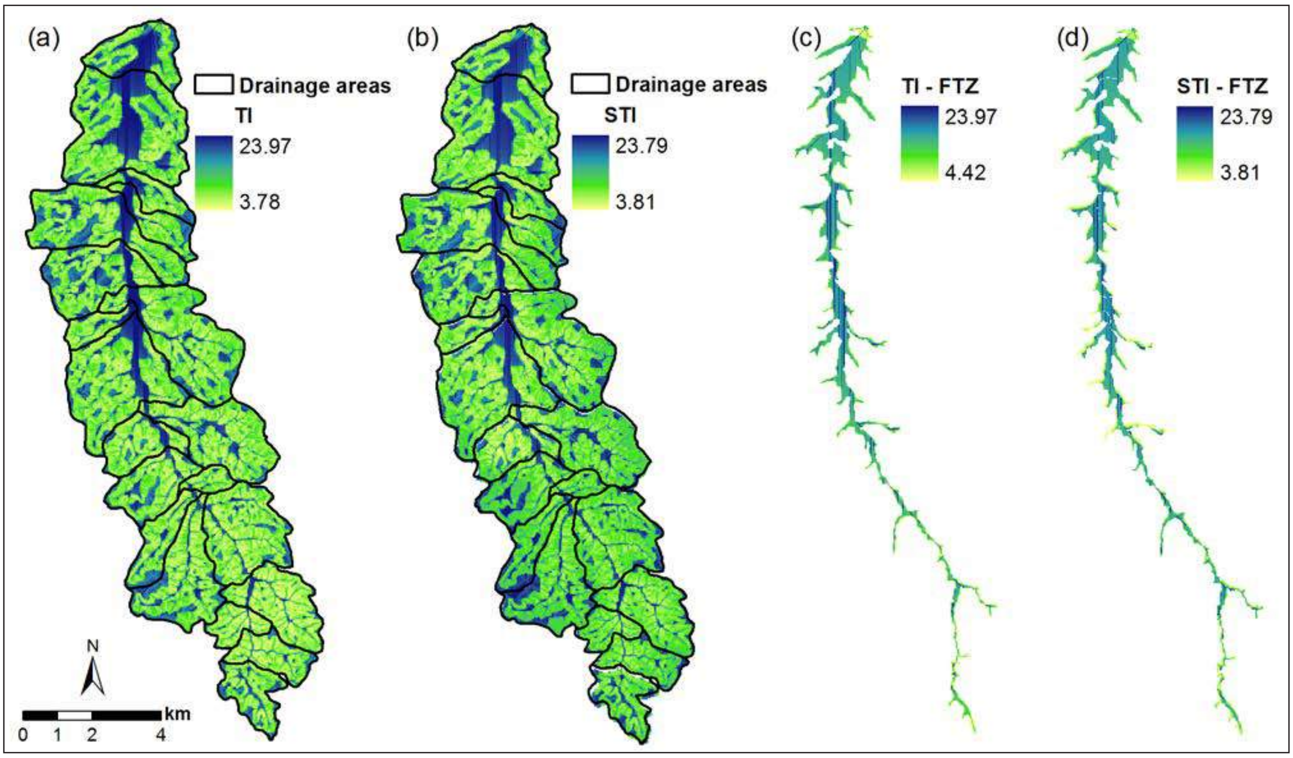

Figure 9. Maps of the indices for the entire BRB and for the FTZ. (a) *TI* for BRB; (b) *STI* for BRB; (c) *TI* for FTZ; and (d) *STI* for FTZ.

Figure 10 shows the changes of *TI*, *STI* and sinuosity of the main river with increasing drainage area. Both indices (*TI* and *STI*) vary similarly along the basin. *TI* increases gradually with the sinuosity from A6 to A20, meanwhile, *STI* remains constant in this region (Figure 10a). It can be thought that from A6 on, *Ks* increases toward basin outlet (Fig. 7), and the slope effect on increasing *STI* is attenuated. In Figure 10b the *TI* and *STI* changes in the FTZ are presented. It is also noted that *TI* increases more rapidly than *STI* from A6 to A20 (basin outlet). However, in this case, both indices demonstrate similar changes to that of the sinuosity.

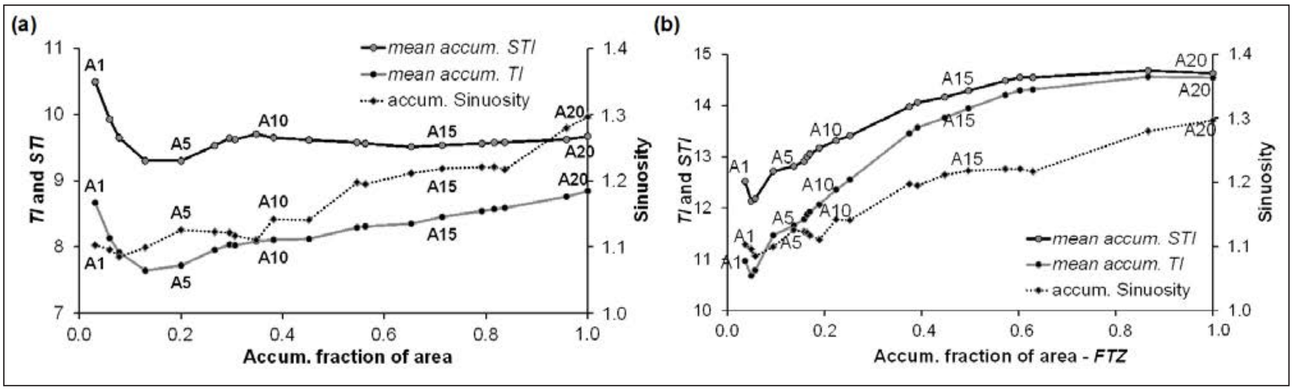

Figure 10. Behavior of the mean accumulated indices (*TI* and *STI*) and sinuosity along the main river: (a) the entire basin; and (b) FTZ

For comparing the changes of *TI*, *STI* and sinuosity more quantitatively, the relationships between the mean accumulated *TI* and *STI* and accumulated sinuosity of the main river at the whole basin level were statistically analyzed (Figure 11). *TI* and sinuosity have a significant correlation (Fig. 11a). On the other hand, there is no significant correlation between *STI* and sinuosity (Fig. 11b). It means that, when the information of *D* and *Ks* is included, the tendency of interaction between river sinuosity and hillslope topography does not exist anymore. The values of *TI* and *STI* are strongly influenced by the slope. The upper part of the BRB basically consists of the drainage areas from A1 to A4. Analyzing the mean value of *TI* in these drainage areas, A1 has the higher one, which permits to consider it as an outlier. It can be explained with the fact that the A1 topography is gentler than the other drainage areas located in the headwater of BRB.

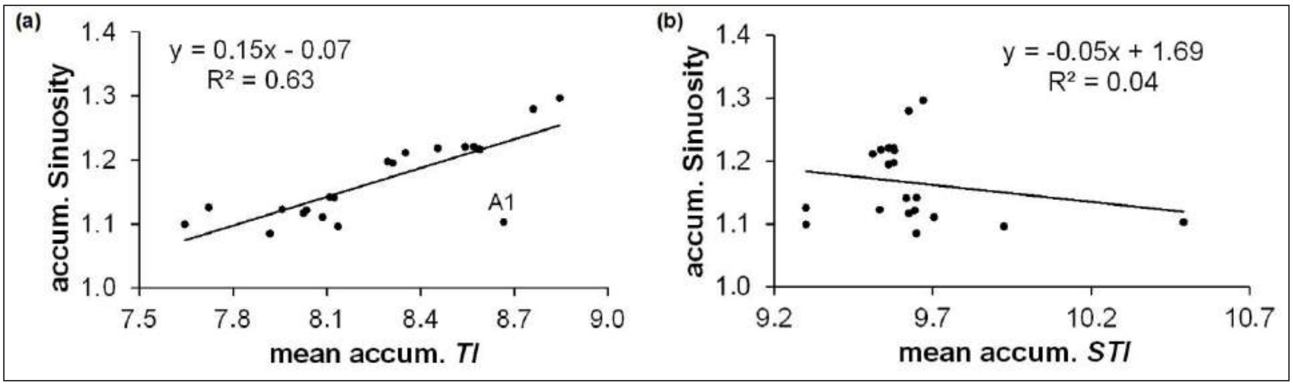

Figure 11. Relationship between the sinuosity of the main river and the mean accumulated indices of the drainage areas. (a) mean accumulated TI, and (b) mean accumulated STI

A similar analysis of such a relationship between *TI*, *STI* and sinuosity was carried out by considering these indices only in the FTZ (Fig. 9c and 9d). There is a significant correlation between the indices and the sinuosity (Figure 11). This fact may imply the more intense interaction between the topography near the main river channel and the sinuosity. Furthermore, this result suggests the potential use of the concept of FTZ for future work about river network. The points corresponding to A1, A10 and A20 in both graphs of Figure 12 show the trend of increasing sinuosity and indices toward downstream. This tendency is also seen in Figure 10b.

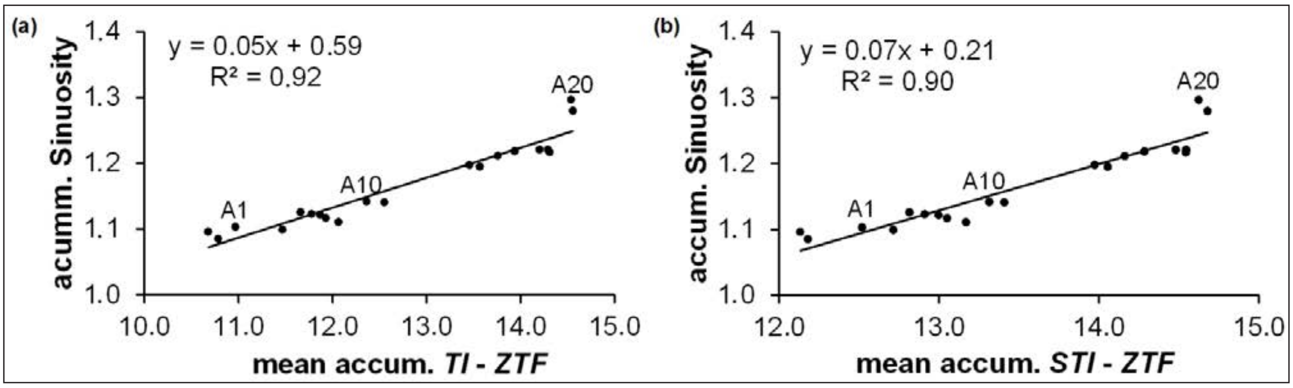

Figure 12. Relationship between the sinuosity of the main river and the mean accumulated indices in the FTZ. (a) mean accumulated *TI*, and (b) mean accumulated *STI*

Based on a Brazilian law (Forest code), the PPA along the main river was delimited and its area was compared with the FTZ (Figure 13). The FTZ and PPA comprise 10% and 3% of the total basin area, respectively. This comparison shows that only in the upper part of the main river the FTZ coincides with the PPA very well and that their difference gradually increases towards the downstream river. In the lower part of the basin, the FTZ width reaches 300 m, while the PPA remains 30-m width. It is worthwhile to note that although the present comparison considered only the areas, the concept of FTZ possesses 3-dimension aspect. Therefore, the more appropriate comparison should be on volumes, which may result in a larger difference between PPA and FTZ.

CONCLUSIONS

The maps of *TI* and *STI* revealed a large variation of these indices in the whole basin. The highest values occurred at cells associated with the channel network and the smaller ones at cells near the top of slopes. *STI* remains almost unchanged even when the slope decreases, because it coincides with areas where *Ks* increases. On the other hand, *TI* increases in downstream direction as the slope decreases.

The analysis of the influence of some soil properties and topography in sinuosity of Bugres river by using *TI* and *STI* showed that these indices can be very useful for understanding the behavior of sinuosity of this river.

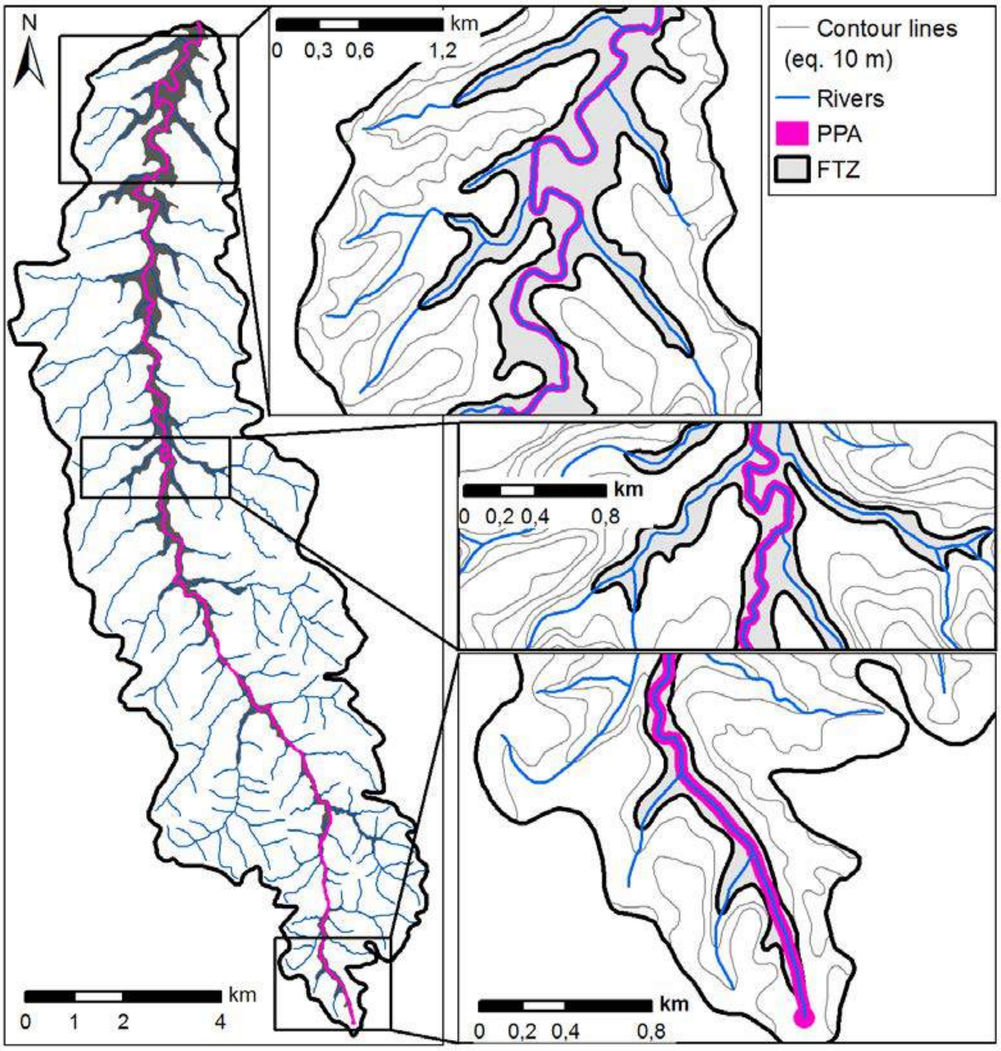

Figure 13. Fluvial Topographic Zone and Permanent Preservation area

The behavior of sinuosity is more strongly influenced by the topography than by soil properties. And this influence becomes more significant only in the FTZ than in the whole basin.

Thus, the FTZ can be defined as the zone along the river where the interaction between fluvial and hillslope processes is more intense. Therefore, it can be thought that the environmental conditions in the FTZ are substantially peculiar and characterized as a mixture of fluvial and hillslope features.

The comparison between FTZ and PPA permits to conclude that the FTZ comprises river meandering dynamics, which is of extreme importance for the preservation of various species of both flora and fauna of the riparian zone. Furthermore, the variable width of the FTZ depending on each river must be considered positive, because it enables capturing rivers' peculiarities.

Furthermore, recently, landscape evolution models have been drawing attention of scientists, both due to technological advances in computer sciences and geotechnology and due to increasing environmental and territorial problems (Tucker & Hancock, 2010). Each model requires information regarding the mechanisms of meandering, relation between topographical indices and river sinuosity, and so on. Therefore, the results obtained in the present study may contribute to the development of such models.

Kolasa & Zalewski (1995) consider that one of the most important aspects identified in their review on ecotones is the scale-dependence. In this way, it is relevant to note that the procedure of delimitation of FTZ in the present study was tested for the scale 1:50,000. In the future study, it will be necessary to test other scales´ maps.

The main characteristic of FTZ is the more intense interaction between fluvial and hillslope processes. In the present work, a method to delineate this zone was proposed, however it can still be modified as the technique is tested with different scales and basins. Nevertheless, the main characteristic of FTZ must be remained.

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