https://rbgeomorfologia.org.br/rbg
ISSN 2236-5664

Revista Brasileira de Geomorfologia

v. 23, nº 4 (2022)

http://dx.doi.org/10.20502/rbg.v23i4.2164

Research Article

A geomorphometric analysis in a mountain environment with the presence of a canyon: Case study of Boi River basin

Análise geomorfométrica de uma bacia montanhosa com presença de cânion: estudo de caso da bacia do Rio Boi

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Recebido: 12/10/2021; Aceito: 20/07/2022; Publicado: 01/10/2022

Abstract: The river channels and the drainage network play an essential role in landscape evolution. Hydrogeomorphic studies provide valuable information to understand river basins and their processes by identifying relevant morphometric factors within river systems. In this sense, the aim of the present study was to carry out a geomorphometric analysis of the Boi River basin. Inside the basin having the Canyon Itaimbeizinho, there are three remarkable parts, Plateau, Hillslope, and Alluvial Plain. For the three parts, Area (*A*), Length of the Main River (*L*), Drainage Density (*Dd*), River Frequency (*Rf*), Sinuosity of the Main River (*Si*), Mean Topographic Index (*TIm*), and Lineament Density (*Lm*) were determined. Also, the Box-Counting method was performed to analyze the fractal dimension of the drainage network (*DF*) and river channels (*df*). Relations between these variables were verified through Pearson correlation analysis and the adjusted coefficient of determination. Parameters such as *A*, *Si*, and *TIm* are related to drainage network development (*DF*). While *Dd*, *Dr*, and *Lm* were associated with the development of river channels (*df*). The study allowed identifying geomorphological characteristics that provide relevant information for analyzing the Boi River basin parts. Geomorphometric studies can complement risk management and prevention studies, applied in the identification of areas with danger potential for the community.

Keywords: Fluvial Geomorphology; Fractal Dimension; Plateau; Hillslope; Plain.

Resumo: Os canais fluviais e a rede de drenagem possuem um importante papel na evolução da paisagem. Estudos hidrogeomorfológicos fornecem informação valiosa para o entendimento das bacias hidrográficas e seus processos, uma vez que identificam fatores morfométricos relevantes dentro dos sistemas fluviais. Portanto, o objetivo deste trabalho foi caracterizar geomorfometricamente a bacia do Rio Boi e as regiões de Planalto, Encosta e Planície (SC/RS). Para as três regiões foram avaliados os fatores: Área (*A*), Comprimento do Rio Principal (*L*), Densidade de Drenagem (*Dd*), Densidade de Rios (*Rf*), Sinuosidade do Rio Principal (*Si*), Índice Topográfico médio (*TIm*) e Densidade de Lineamentos (*Lm*). Foi aplicada a metodologia de Box-Counting para avaliação da dimensão fractal da rede de drenagem (*DF*) e dos canais fluviais (*df*). Verificou-se mediante análises de correlação de Pearson e o coeficiente de determinação ajustado que *A*, *Si* e *TIm* estão relacionados com o desenvolvimento da rede de drenagem (*DF*), enquanto *Dd*, *Rf* e *Lm* estiveram mais associados ao desenvolvimento dos canais fluviais (*df*). O estudo permitiu a identificação de características geomorfológicas que fornecem informação relevante para a análise das diferentes regiões da bacia do Rio do Boi. Estudos geomorfometricos tem potencial de complementar estudos de manejo e prevenção de risco, aplicáveis na identificação de áreas com potencial perigoso para a comunidade.

Palavras-chave: Geomorfologia Fluvial; Dimensão Fractal; Planalto; Encosta; Planície.

1. Introduction

The landscape evolution comprises changes in the environment due to climatic, anthropic, and geological factors interactions that respond under a non-linear dynamic, and these interactions are constantly co-evolving with human action (BEVEN, 2015). Some examples of landscape evolution in mountain environments are basins formation, slope evolution, and fluvial alterations. Within the elements forming the landscape at the basin scale, river channels and their network play an active role (BRIERLEY and FRYIRIS, 2005). River channels are responsible for draining water within a specific area and can form robust networks according to their spatial and temporal distribution (CHRISTOFOLETTI, 1980). Thus, the erosive power of water organizes the landscape configuration and evolution. Therefore, hydrology or hydrogeomorphology helps to understand landscape processes, given the relationship between water and landscape.

Hydrology is defined as the science that deals with water issues on Earth, its occurrence, circulation, distribution, physical-chemical properties, and the reaction with the environment, including the relationship with living things (FCST, 1962). In this sense, hydrology encompasses many strands of knowledge such as geology, geography, ecology, and anthropology. Thus, sciences like hydrogeomorphology (SCHEIDEGGER, 1973) are about hydrology and geomorphology joint studies, which over time have been strengthened. According to Goerl et al. (2012), hydrogeomorphology is a science that seeks to understand how hydrological processes contribute to the formation and evolution of the landscape and how landforms control hydrological processes at different temporal and spatial scales. Thus, the characterization of the mountain environment in terms of hydrogeomorphology enables the recognition of morphometric influences of the landforms (i.e. slope, kinds of soils, geostructures) that trigger extreme events such as floods and mass movements (COCO et al., 2015, ZWOLIŃSKI and GUDOWICZ, 2015, ZHANG et al., 2020). In both urban and rural territorial planning, morphometric influences must be considered.

The main objects of geomorphological studies are geomorphic units (morphogenesis) and mass movements (morphodynamics) (FORERO-OSPINO and DUARTE-DELGADO, 2019). Morphogenesis studies the origin, constant evolution, and shape of geomorphic elements. This science describes topographical and geometric aspects that define the natural landscape structure. (MONTANARI et al., 2013). Among the most studied geomorphological parameters describing basins, altitude, slope, topographic moisture index, and convergence index stand out (MOTA et al., 2013; BURIAN, 2015; ZWOLIŃSKI and GUDOWICZ, 2015). However, other elements such as the lithology and soil type of the basins influence geomorphological dynamics, too (COCO et al., 2015). There can be seen many parameters within the basins' dynamics. Therefore, the complete understanding of their processes is a challenge. Thus, the challenging task of characterizing and understanding river basins for professionals in the environmental sciences is recognized because nature responds in disproportional ways to extreme events. In this sense, many methods to represent the complex relationships and forms of natural systems are still not well developed with empirical and mathematical ways.

One of the scientific concepts developed in the '70s that broadened the understanding of natural/water systems is the fractal geometry. The mathematician Benoît Mandelbrott (1975) postulated fractal geometry referring to an object that maintains a structure identical to the original while the scale under which it is analyzed is altered (ASSIS et al., 2008). In the advances in fractal geometry, fractal dimensions provided the possibility of describing landscape characteristics (XU et al., 1993) and contributing to the simulation of river drainage network evolution (WANG et al., 2020). In this sense, it was possible to analyze irregular forms of drainage networks and to establish relationships with hydrological processes (LA BARBERA and ROSSO, 1987; TARBOTON et al., 1988; ROSSO et al. 1991; TARBOTON, 1996; ROTH et al. 1996). Fractal analyses of basins verified their multi-fractality, i.e., different values between the fractal dimension for the river channels (df) and the entire network (DF) of the same basin (RODRÍGUEZ-ITURBE and RINALDO 1997). Hence, fractal studies may contribute to understanding processes in mountainous environments together with sciences such as geomorphology, hydrology or hydrogeomorphology.

Deeping into the knowledge of basins in geomorphological terms allows us to analyze and reduce the risk of hydrological disasters. Also, it is possible to identify hazard areas. In this context, the aim of the present study was to carry out a geomorphometric analysis of the Boi River basin and its three different internal regions, emphasizing the fractal dimension of a mountain basin characterized with a canyon. This work trusts that this type of research can support the integrated management of water resources and of river basins (GONZÁLEZ-ÁVILA et al., 2021) and help the development of sociogeomorphological approaches in territory management (i.e., RAMOS, 2018).

2. Study Area

The study area is the Boi River basin (111.65 km²), located on the border between the states of Rio Grande do Sul and Santa Catarina, southern Brazil. This basin is within the Serra Geral Formation and is characterized by the presence of escarpments and canyons (PAIXÃO et al., 2021), being an important region for ecotourism activities (MAZZALI et al., 2021). It has altimetry between 80 and 1070 m, and has scarps up to 700 m to the walls that make up the Itaimbezinho canyon, a great tourism attraction wholly located inside the study area. The basin is mostly situated in the Aparados da Serra National Park (PNAS), which is an essential unit of environmental protection of the Serra Geral region. The PNAS faces part of the significant set of canyons of South America, being part of the most extensive canyon chain in this continent.

Based on the classification of the Brazilian landforms proposed by Ross (1985) and the characteristics of the Boi River basin, the present study divided the basin into three parts: i) Plateau; ii) Hillslope; and iii) Plain (Figure 1, SIRGAS 2000 - 22S Coordinates). For geomorphological characterization of this basin, each part was evaluated based on geomorphometric parameters such as Area (*A*), Length of the Main River (*L*), Drainage Density (*Dd*), River Frequency (*Rf*), Mean Topographic Index (*TIm*), and Sinuosity of the Main River (*Si*), because they are widely used in the description of river basins of different scales (ALTIN and ALTIN 2011; MARTÍNEZ and DÍAZ, 2011).

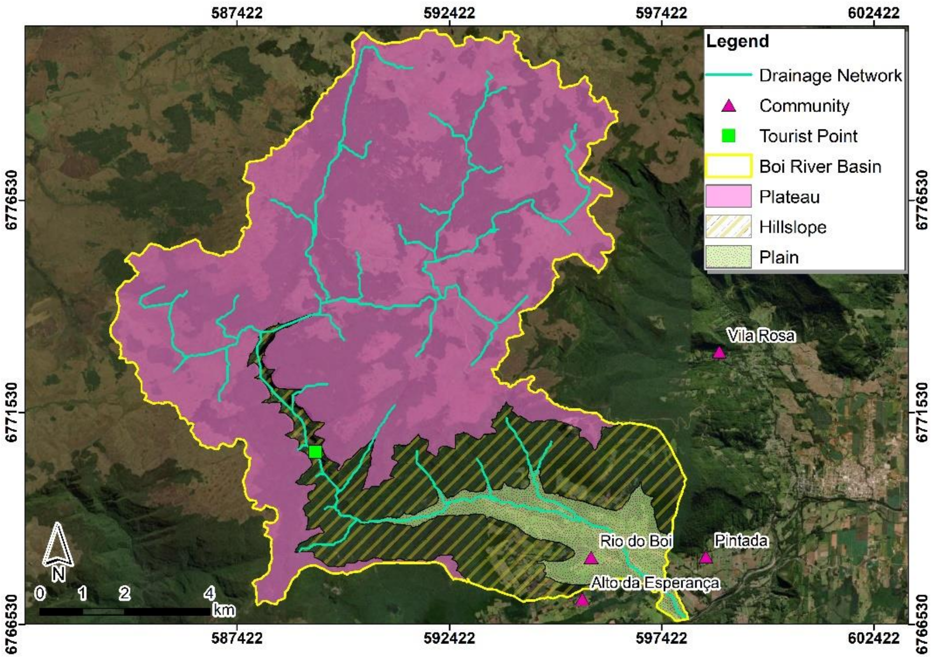

Figure 1. Classification of the Boi River Basin landforms.

In the Plateau part, the main tributaries of the basin (the Arroio Água Comprida creek and the Perdizes creek) encounter and form the Perdizes River (CAMPAGNOLO et al., 2021) which constitutes one of the main waterfalls into the canyon, the Andorinha's waterfall. The basin's predominant vegetation is the Atlantic Forest biome and includes Araucaria Forest in the Plateau part (CAMPAGNOLO and KOBIYAMA, 2021). The Plateau part ends at a sudden descent, giving way to the Hillslope.

The Hillslope is a heavily rugged part in which the humid climate has largely eroded it. This part is characterized by a typical mountainous environment, with steep hillslopes, entrenched drainage channels, and longitudinal variation in channel geometry, according to the mountain characteristics described by Paixão and Kobiyama (2019). The shallow soil layer supports rupicolous vegetation and nebular thickets (FALKENBERG, 2003), present in rocky and steep walls with low-height trees and small leaves.

The Alluvial Plain or Plain has been frequently modified over the last decades, as described by Vasconcellos et al. (2021). In this part, the replacement of native vegetation by agricultures such as beans, bananas, and smoke. According to Paixão et al. (2021), this part has a vast history of extreme hydrological events, with the main events occurring in 1903, 1911, 1947, 1974, 1995, 2007, and 2020.

Geologically, the basin is in the Serra Geral Formation, characterized by volcanic rocks and spills. Serra Geral basalt flows are characterized by fractures or discontinuities in the rock block, which influences soil stability and fluid percolation routes (WILDNER, 2006). According to Köppen's classification, the regional climate is Subtropical Mesothermal Humid (Cfa), with hot summers and cold winters in the lower parts of the basin, especially on the hillslopes and the alluvial plains. The climate is also Moist Mesothermic Temperate (Cfb) with cold winter and mild summer (MORENO, 1961; PANDOLFO et al., 2002; CASTIGLIO et al., 2021), specifically in Plateau. The mean annual precipitation of the basin is approximately 1800 mm.

3. Materials and Methods

3.1. SIG Data

The digital elevation model (DEM) was obtained from the Advanced Land Observing Satellite (ALOS), Phased Array type L-band Synthetic Aperture Radar sensor (PALSAR) - (https://search.asf.alaska.edu/), with a spatial resolution of 12 m, as well as the DEM of the State Secretariat for Sustainable Economic Development of the Government of the State of Santa Catarina (SDS), with the spatial resolution of 1 m. The basin was delimited through the construction of a mosaic of DEM (12-m and 1-m), and the drainage network was generated. For dimming bias due to DEM´s resolution, the drainage network was visually compared and corrected according to satellite images of the study area. By using Global Mapper software, a Shuttle Radar Topographic Mission (SRTM) image was extracted, which allowed the identification of linear features associated with geomorphological features in the study area. The software used for GIS data processing was ArcGIS 10.5 software licensed by the Federal University of Rio Grande do Sul (UFRGS).

3.2. Geomorphometric characterization

GIS tools were implemented to extract the data of interest from the constructed DEM and to identify geomorphic features. Geomorphometric parameters *A*, *L*, *Dd*, *Rf*, *TIm*, and *Si* were determined. According to their definitions, these parameters were calculated with the following equations (Eq. 1- Eq. 4):

$$D_d = \frac{\sum L_i}{A} \tag{1}$$

$$R_f = \frac{\sum N}{A} \tag{2}$$

where *N* is the total number of channels.

$$Si = \frac{L}{L_{total}} \tag{3}$$

where L_{total} is the shorter distance between begin and end of the river from an upstream to a downstream point in a straight linein km. The *Si* value represent the 'Total Sinuosity'described by Mueller (1968).Here it should be noted that the present work evaluated only the main river of each defined region to calculate *Si* and *L*. It is due to each part present several ramifications in the drainage network.

$$TI = \ln\left(\frac{\alpha}{tan\,\beta}\right) \tag{4}$$

where α is the relation between *A* and Perimeter (P) of the analyzed part of the basin in m2/m, and β is the slope of the part in degrees. The Topographic Index (*TI)* identifies areas with potential flow accumulation that can generate surface or subsurface runoff (AMBROISE et al., 1996), so this index is derived from DEM information.Although the *TI* value is generated for each pixel, the average value of each region was the data considered in the calculations as Mean Topographic Index (*TIm*) established from the software metrics.

The values were obtained by applying the tools of the spatial analysis extension (Spatial Analyst tools) and the raster calculator (Raster Calculator). The calculation procedure and used software tools are shown in Figure 2.

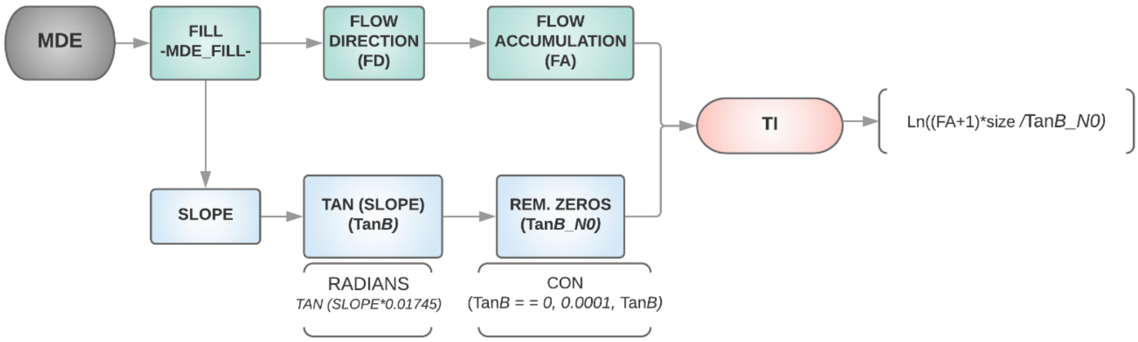

Figure 2. Calculation flowchart to *TI*.

3.3. *Lineament Density*

Among the analyzed parameters, the lineament is a simple cartographic representation of a line on the surface, such as topography, vegetation, or hydrography (LATTMAN & PARIZEK, 1964).For the Boi River basin, type 2 lineaments were identified (STRIEDER & AMARO, 1997) from an image provided by the SRTM and processed on a 1:50.000 scale. The type 2 lineaments also are called negative geomorphological features (RAMLI ET AL., 2010). The distinction of the lines was based on the contour lines (WEBER and HASENACK, 2007) and the drainage network. The latter is extracted from the DEM described in section 3.1. In each part, the number of present lines was recorded. Also, the value of lines per unit area was called *Lm*.

3.4. *Fractal analysis of parts*

The Box-counting method, described by Goodchild (1982), is widely used in fractal dimension determination (SCHULLER et al. 2001; VESTENA & KOBIYAMA 2010; da SILVA & de SOUZA 2010; CABALLERO et al., 2020). The method consisted of creating a grid that covered the area of interest, the drainage network, and the river channels of the Boi River basin. In this way, the figure was divided according to the grid, generating a lot of "boxes" with side length (*r*) and the total number of boxes (*N(r)*), in which that the boxes intersecting the target figure were counted (Figure 3).

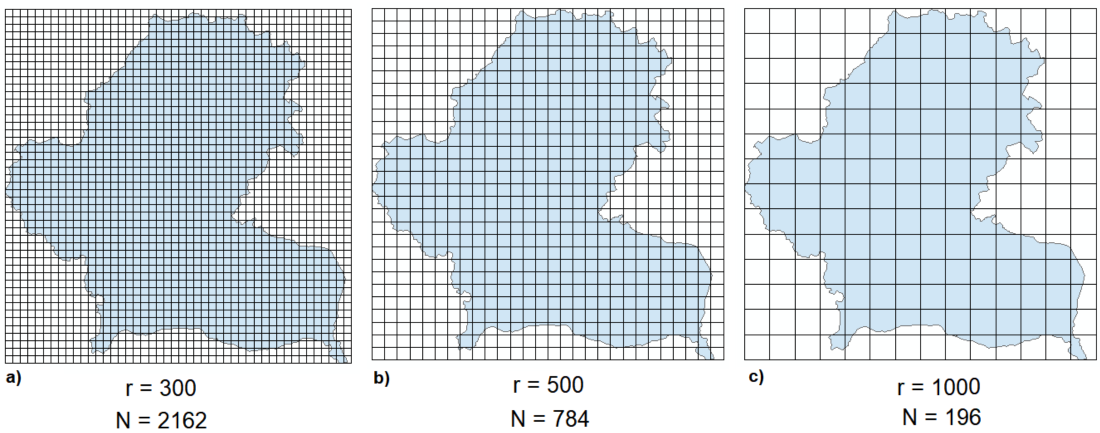

Figure 3. Box-Counting of Boi River basin with different box sizes: (a) r = 300 m and N =2162; (b) r = 500 m and N =784; (c) r = 1000 m and N =196.

The values of *r* and *N(r)* are associated by the Eq. 5 and allow to determine the fractal dimension (*DF*):

$$DF = \lim \frac{\log N(r)}{-\log (r)} \quad (5)$$

A log-log graph is used, where the values of log *N(r)* and log *(r)* are plotted so that a linear relation is generated whose slope (-*k0*) represents the fractal dimension:

$$\log N(r) = -k_0 \log(r) + \log\mu \quad (6)$$

According to Tarboton et al. (1988), to calculate the fractal dimension of river courses (*df*) and the drainage network (*DF*) it is recommended to use grids of *r* with values between 15 and 125 mand between 250 and 1000 m, respectively. Thus, 8 different *r* values, corresponding to 25, 50, 75, 100 for *df*, and 150, 300, 500, 1000 for *DF* were used for the fractal analysis.

3.5. *Relationship between geomorphometric parameters and fractal dimension*

Pearson's correlation and the adjusted coefficient of determination (R^2aj) between the fractal dimensions (*df* and *DF*) and the geomorphometric parameters (*A*, *L*, *Dd*, *Rf*, *Lm*, *Si*, *TIm*) were applied, totaling 14 relationships. Because of the data presenting very different scales, log10 was used to mitigate errors due to different magnitudes. Furthermore, Cluster Analysis (the Average Linkage Method and the Correlation Distance Measure) was applied to reduce the group of variables in two groups with maximum similarity.

4. Results and Discussion

4.1. *Conventional characterization of parts*

Table 1 shows a geomorphometric characterization of the whole basin as well as of the three parts delimited in the Boi River basin.

Table 1. Geomorphometric characteristics of the Boi River basin parts

Part	N. Channel	*A* km²	*L* km	*Dd* km⁻¹	*Rf* km⁻²	*Si*	TI_m	L_m km⁻¹
Plateau	20	81.75	12.11	0.52	0.25	1.58	6.96	0.49
Hillslope	7	21.88	7.05	0.54	0.32	1.40	4.74	0.91
Alluvial Plain	6	8.02	9.23	1.56	0.75	1.17	4.92	0.62
Boi River	33	111.65	28.50	0.73	0.30	2.38	11.10	0.58

The Plateau part is the widest within the Boi River basin. The main river of the basin (28.50 km) has its longest path in the Plateau area (12.11 km), followed by the Alluvial Plain (9.23 km). An approximate 2:1 ratio was identified between *Dd* and *Rf*, representing the predominance of a low number of channels compared to the total length of the river channels. Thus, the basin regions proved to be regularly drained areas where the tendency to accumulate water in a specific area is low. It was verified through the Dd between 0.52 and 1.56 km/km2[A1], similar to findings described by Caballero et al. (2020) on sub-basins of the Mampituba River Basin in a nearby area regarding the present study. This water accumulation condition is suitable for a general characterization of the region but is maybe different for geomorphic units assessment in the Boi river, where pools are formed (PAIXÃO, 2021). The determined values of *Rf* varying from 0.25 to 0.75 channel/km² imply moderate susceptibility to flooding under normal rainfall conditions. However, extreme rainfall events in the basin generated channel modification in the area in 2020 (PAIXÃO et al., 2021). Such alterations might be related to the influence of geology, topography, and vegetation cover, but these relationships need to be investigated in future studies.

The Hillslope and Alluvial Plain parts of the Boi River basin are characterized as lightly meandering channels according to the obtained results. Therefore, the curvatures of rivers (sinuosity) and geomorphic units can be associated, which means a higher presence of geomorphic units when sinuosity properties are dominant. That condition is supported due to block rock fractures of Serra Geral Formation. The Boi River basin shows a *Si* equal to 2.38. It indicates anastomosed or meandering river (GARCIA, 1992). In many reaches in the Boi River (i.e., Alluvial Plain), there are bars or islands that are proper of this kind of river. On the other hand, the main river in the Plateau region is considered meandering according to the calculated index by GARCIA (1992). The study of the meandering of the river allows understanding some processes of the basin, such as lateral erosion and island emergence (OLLERO OJEDA, 1996). The geomorphology of the basin could be affected by several anthropic and natural phenomena. For example, the Itaimbezinho canyon has the potential to present a channel incision. That phenomenon can alter the sinuosity in the Boi River because it has already been verified in other geomorphic features (i.e., ZHANG et al., 2020). Another natural phenomenon that modifies the basin geomorphology is the mass movements. In the study area we can identify some conditioning factors of mass movements described by Pinto et al. (2013), such as the presence of faults, fractures, and high slopes. The Hillslope part is a very rugged zone with wide variation in the lengths of the channels. It has low sinuosity (straight rivers), a factor that facilities rock weathering then mass movement.

The *TIm* values showed that there is an expressive accumulation of moisture in the Plateau, which confirms that it acts as a "water tower" (VIVIROLI et al., 2007) and freshwater supplier. In addition, the Hillslope part showed a low tendency of moisture accumulation (*TIm* = 4.72), which is consistent given the larger slopes and shallow soils, conditions that promote rock erosion, and landscape evolution. The *TIm* in the Alluvial Plain part confirmed the drainage capacity, which was also verified with the parameters Rf and Dd. It was observed that *TIm* was similar between Alluvial Plain and Hillslope. From an all perspective of the Boi River has an expressive accumulation of moisture. The Basin is an area with a floods tendency especially in the Alluvial Plain part. The effects of such a watercourse can be exacerbated by anthropogenic actions, especially in Alluvial Plain, such as modification of the river channel, deforestation, and land-use change.

The value of *Lm* is higher in the Hillslope part, followed by the Alluvial plain and finally the Plateau. In this study, negative geomorphological features were identified as was expected due to their relationship with joints, faults, valleys, and rivers. The *Lm* is well-related to drainage networks and their development. In this sense, we observe that the high *Lm* value is explained due to the presence of the Itaimbeizinho Canyon which is possible to represent in the cartography and show a notable and different feature among the other regions of the basin. Due to lineaments analysis is useful to landslide hazard mapping (RAMLI et al., 2010) the *Lm* parameter could be useful in risk and management studies in the area. Furthermore, it was identified that the geomorphic parameters like slope and sinuosity strongly control the drainage network of the Hillslope part, which makes this specific area very susceptible to a mass movement. In the opposite case, the Plateau shows lower *Lm* probably due to the presence of large rocky blocks in the region that has under control over the drainage network when compared to other regions. The areas delimited here have lines crossing different parts. Thus, the landform classification proposed by Ross (1985) should be carefully applied because the altitude cannot be the only parameter to delimit different landforms. Characteristics such as hillslopes and field data (such as GPS information and photographic record) are two kinds of data that we consider useful in detailing the landform delimitation.

4.2. Fractal characterization of parts

The fractal dimensions were calculated to describe the morphology of the fluvial channels and the drainage network of the Boi River Basin (Table 2).As Rodriguez-Iturbe and Rinaldo (1997) mentioned, multifractality refers to a basin with different values of *DF* and df (Table 2). However, the multifractality in the Boi River basin allows us to observe different drainage and channel river configurations between the three regions of the basin, reflected in different values of the fractal dimension of the three regions.

Table 2. Fractal Dimension in the study area

Part	*DF*	*Df*
Plateau	1.8353	1.0114
Hillslope	1.6909	1.0060
Alluvial plain	1.6208	1.0152
Boi River	1.9090	1.0147

The correlation between *DF* and *df* was assessment. The correlation was equal to 0.0638 and the R^2 adjusted equal to 0. These values verified that the *DF* and *df* do not have a correlation between them. These two parameters should be considered like geomorphic different parameters useful to describe a basin.

The fractal dimension of the drainage network has a different value among the regions. It could be possible to think in the *DF* of Boi River basin like an average between the regions. However, it was verified that the *DF* of the Boi River basin is not average, and it is the higher value of *DF*. The *DF* is possible to be associated with area extension.From low df values (*df*~1) and according to the *Si* already discussed, the river channels of the Boi River basin can be described as having low sinuosity, especially in the Hillslope part (*Si* = 1.40) in that the large altimetric variation (80-1070 m) prevents the meandering. In addition, the cartographic representations with *Lm* also allowed verifying the high linearity in the Hillslope part. The aforementioned demonstrates that the drainage network in the basin runs over a geologic fault and the control of geology over the drainage. Although the *df* values do not vary widely among the basin parts, the Alluvial Plain seems to be with the most outstanding development of river courses, coherent with *Dd* and *Rf*.

Fractal dimensions for drainage network (*DF*) were found between 1.62 and 1.84, values like those found by Tarboton et al. (1996) in different conditions from those presented in this study. Tarboton et al (1996) study assessment the Buck Creek basin with 606 km^2, bigger than Boi River basin (111.65 km^2). Also, the DEM used to build the drainage network in the former study has a 30-m resolution, while in our study was a mosaic built with 1-m and 12-m of resolution. Although the fractal dimension is not dependent on scale factors, the build of the drainage network can be affected. Thus, detailed geographic information allows us to analyze a little area. Formerly it would be a limitation because poor resolution image data can not detail small areas. According to the DF values, the drainage network of the Boi River basin shows a high degree of development (*DF* near to 2). In this sense, the relationship between the geomorphological domain of the Serra Geral Escarpment, identified by IBAMA (2019), and the drainage network in the study area should be noted. The environment of the Serra Geral Escarpment involves a broad interaction between hydrogeomorphological factors, where there is the presence of rocks with many cracks and fractures that compromise the slope stability. The fractal dimension for river channels (*df*) founded was between 1.01 and 1.02. These results are close to those reported in other studies that also considered small basins and analyzed the relationship between catchment area and fractal dimensions (i.e. HJELMFELT, 1988).

In studying the fractal dimension of the Maquiné river basin, which is nearby to the present study area, Tavares et al. (2017) reported df=1.008 and DF=1.975. These values are similar to those obtained in this study. The Boi River was also studied by Caballero et al. (2020). However, in their study, the Boi River is referred as Pavão River, an additional name of the same river. By using digital terrain model data from the SRTM with a resolution of 30-m, Caballero et al. (2020) demonstrated the application of the box-counting method 6 sub-basins and the relationship of the fractal dimension with some hydromorphometric characteristics. The authors show the *A* value has a positive correlation with the fractal dimensions, which is also obtained in the present study. Our methodology identified geomorphic regions with different features. The fractal dimensions for the Boi River basin were similar (*DF* =1.80; *df* = 1.22) to those of Caballero et al. (2020), even though their methodology differs from the present one.

4.3. Fractal characterization of parts

The Cluster Analysis identified two groups of the analyzed variables with 93.19% and 40.26 % of similarity level (Figure 4 and Table 3). The most similar group is composed of *DF*, *A*, *L*, *TIm*, *Si* (blue color). The second group is *df*, *Dd*, *Rf*, and *Lm* (red color). These groups are coherent with the results of statistical relations explained below. Also, the statistical relations (Pearson coefficient and R2 adjusted) between geomorphometric parameters and fractal dimensions were evaluated (Table 4).

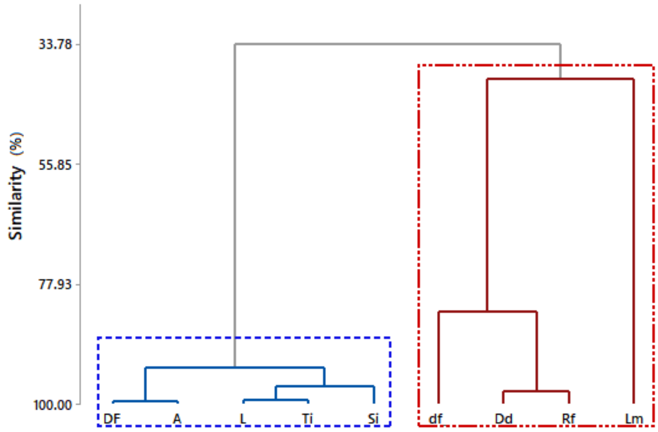

Figure 4. Cluster Analysis of the variables. Dendrogram.

Table 3. Similarity Level and Distance Level

Step	Similarity Level (%)	Distance Level
1	99.41	0.01
2	99.11	0.02
3	97.51	0.05
4	96.64	0.07
5	93.19	0.14
6	82.94	0.34
7	40.26	1.19
8	33.78	1.32

Table 4. Relations between fractal dimensions and physic characteristics of basin.

Parameter	Fractal Dimension	Pearson	R^2_{aj}
A	***DF***	**0.99**	**0.96**
	df	-0.14	0
L	*DF*	0.84	0.55
	df	0.45	0
D_d	*DF*	-0.56	0
	df	0.80	0.47
R_f	*DF*	-0.79	0.43
	df	0.60	0.02
S_i	***DF***	**0.93**	**0.80**
	df	0.04	0
TI_m	***DF***	**0.93**	**0.78**
	df	0.38	0
L_m	*DF*	-0.53	0
	df	-0.64	0.11

Parameters such as *A*, *Si*, and *TIm* presented a high degree of linear correlation with *DF* and expressive proportions of variables between R2 adjusted. According to the Cluster Analysis, there are also parameters more relevant to the drainage network. In practical terms, a well-developed drainage network is associated with extensive areas, moderate sinuosity, and a moderate to high accumulation of moisture. Thus, areas with similar characteristics to the aforementioned have the potential to have a well-developed drainage network. In this sense, the Plateau region is showed as a different region inside the study area due to its characteristics. The parameters *Dd*, *Rf*, and *Lm* have an inverse linear statistical relationship with *df*. However, the R2 set in df cases is not relevant. The result of low R2 adjusted for the *Dd*, *Rf*, and *Lm* parameters is observed in the Cluster Analysis. The dendrogram showed less similarity than the first group. The channels configuration (*Dd* and *Rf*) in the Boi River basin was well-associated with *df*. Noteworthy in Figure 4 that *Dd* and *Rf* are very close to river channels (*df*) (similarity = 82.94 %). The *df* demonstrates to be a good descriptor of channels river configuration in the mountain basin. The high *df* values indicate a high proportionality of river courses with respect to the area of the basin. Thus, the development of river channels could be estimated by *df*, this is an advantage of the fractal method to assess geomorphometry in a basin. The Alluvial Plain was the region with higher *Dd* and *Rf* as well as higher *df*. This kind of relationship allows us to identify the differences inside a mountain basin. These characteristics are sometimes neglected in studies considering homogeneous features inside a certain study area. It is observed that the parameters (*A*, *Si*, *TIm*, *Dd*, *Rf*, and *Lm*) associated with fractal geometry may provide important geomorphometric information. Furthermore, they can be useful to understand the hydrogeomorphic processes in the mountain basins. As evidenced by Ramírez Hernández et al. (2017), the present study also demonstrates that geomorphometric parameters are highly related to tectonic and structural basin properties and determine the characteristics of river drainage and basin. Thus, the boi river landscape is molded by geomorphic and river drainage interactions.

5. Final Remarks

The Boi River basin is well known because of its sightseeing attractions, especially holding a canyon environment in its extension, drawing attention to the hydrogeomorphological community. The present work demonstrated how geomorphic features could be characterized with geomorphmetric parameters and the easy way to obtain their values in this basin.

The fractal dimension study supports the analysis of the drainage network and river channels. According to the fractal theory, the determined values of *DF* and df (*DF*>1.5; *df* ~1) were coherent. As observed in the Boi River basin, the different geomorphic configurations in the study area may contribute to establishing particular hydrogeomorphic dynamics. Existing lineaments in the Basin well matches with the river channels development. For example, the presence of the Itaimbezinho Canyon is a notable feature of the Hillslope region and leads to hydrogeomorphicly-differentiated processes. River channels with high fractal dimensions (*df*) can be associated with the presence of tectonic structures. These facts confirm that the geological features influence on geomorphic ones. The geomorphic structures, as the walls of the Canyon, where the interior massif is fractured usually facilitated to triggering of mass movements so is a factor to consider to natural processes. Historically, the Alluvial Plain region is prone to the flooding situation. It was verified by high df value and other parameters such as *Dd* and *Rf*. Also, Alluvial Plain has river channels slightly straight. The parameters *A*, *Si*, *TIm*, *Dd*, *Rf*, and *Lm* have high correlation with fractal geometry and can be considered to get important geomorphometric information.

Considering the integrated management of water resources and mountain environment, geomorphometric analysis assists in understanding the processes and better identification of the bordering areas between the different landforms of a basin. Consequently, this type of investigation will permit to correctly define the priority areas for the preservation of natural equity and areas susceptible to extreme hydrological events.

Author Contributions: Idea I.G.A and M.K.; methodology, I.G.A and M;K.; software, I.G.A; formal analysis, I.G.A and M.K.; research, I.G.A., M.A.P and M.K.; data preparation, I.G.A; manuscript writing, I.G.A; review, M.A.P, M.K.; supervision, M.A.P and M.K.; All authors read and agreed with the published version of the manuscript.

Funding: This research receive external funding by scholarships by CAPES/ANA nº16/2017 (Financial code 001).

Acknowledgments: To the Federal University of Rio Grande do Sul –UFRGS for granting full infrastructure to carry out a doctorate in water resources and environmental sanitation in the Postgraduate Program of the Hydraulics Researches Institue - IPH.

Conflict of Interest: The authors declare no conflict of interest.

References

1. ALTIN, T., B.; ALTIN, B., N. Drainage morphometry and its influence on landforms in volcanic terrain, Central Anatolia, Turkey. **Procedia-Social and Behavioral Sciences**, v. 19, p. 732-740, 2011. DOI: 10.1016/j.sbspro.2011.05.192
2. AMBROISE, B.; BEVEN, K.; FREER, J. Toward a generalization of the TOPMODEL concepts: Topographic indices of hydrological similarity. **Water Resources Research**, v. 32, n. 7, p. 2135-2145, 1996. DOI: 10.1029/95WR03716
3. ASHMORE, P. Towards a sociogeomorphology of rivers. **Geomorphology**, v. 251, p. 149-156, 2015. DOI: 10.1016/j.geomorph.2015.02.020
4. ASSIS, T. et al. Geometria fractal: propriedades e características de fractais ideais. **Revista Brasileira de ensino de física**, v. 30, n. 2, p. 2304.1-2304.10, 2008. DOI:10.1590/S1806-11172008000200005
5. BEVEN, K. What we see now: Event-persistence and the predictability of hydro-eco-geomorphological systems. **Ecological Modelling**, v. 298, p. 4-15, 2015. DOI: 10.1016/j.ecolmodel.2014.07.019
6. BRIERLEY, G. J.; FRYIRS, K. A. **Geomorphology and river management: applications of the river styles frameweork**. Oxford: Blackwell, 2005. 398p. DOI: 10.1002/9780470751367
7. BURIAN, L.; MITUSOV, A. V.; POESEN, J. Relationships of attributes of gullies with morphometric variables. **Geomorphometry**, v. 1, p. 111-114, 2015.
8. CABALLERO, C. et al. Dimensão fractal e análise geomorfológica de bacias hidrográficas brasileiras. **Revista de Gestão de Água da América Latina**, v. 17, n. 2020.DOI: /10.21168/rega.v17e3
9. CAMPAGNOLO, K.; KOBIYAMA, M. Woody debris characterization in a small basin with araucaria forest. **Revista Brasileira de Geomorfologia**, v. 22, n. 2, p.463-474, 2021. DOI: 10.20502/rbg.v22i2.1984
10. CAMPAGNOLO, K.; VASCONCELLOS, S.; CASTIGLIO, V; FAGUNDES, M.R.; KOBIYAMA, M. Aplicação do Tank Model como Ferramenta de Gestão na Bacia do Rio Perdizes – Cambará do Sul/RS. **Revista Brasileira de Geografia Física**, v.14, n.2, 2021.DOI: /10.26848/rbgf.v14.2.p1143-1158
11. CASTIGLIO, V.S.; CAMPAGNOLO, K.; KOBIYAMA, M. Análise da evapotranspiração potencial no município de Cambará do Sul/RS. **Geonorte**, 2021.DOI: /10.21170/geonorte.2021.V.12.N.39.26.43
12. CHRISTOFOLETTI, A. **Geomorfologia**. São Paulo: Ed. Edgard Blucher, 1980. 188p.
13. COCO, L.; CESTRONE, V.; BUCCOLINI, M.Geomorphometry for studying the evolution of small basins: an example in the Italian Adriatic foredeep. In: Jasiewicz J., Zwoliński Z., Mitasova H., Hengl T.(Eds).**Geomorphometry for Geosciences**, 2015, p. 107-110.
14. DA SILVA, Míriem Martins; DE SOUZA, Wallysonn Alves. Dimensão Fractal. **Revista Eletrônica de Matemática**, n. 2, 2010. ISSN 2177-5095
15. FALKENBERG, D. D. B. **Matinhas nebulares e vegetação rupícola dos Aparados da Serra Geral (SC/RS), sul do Brasil.**DoctoralDissertation - Universidade Estadual de Campinas, Instituto de Biologia, Campinas, SP. 2003.558p. Disponível em: <http://www.repositorio.unicamp.br/handle/REPOSIP/315046>. Acesso em: 06 abr. 2021.
16. FORERO-OSPINO, O.; DUARTE-DELGADO, W.Identification and characterization of the geomorphology (geomorphological environments and units) of the Sheet 121-Cerrito, Colombia, applied to landmass movements, scale 1: 100.000. **Boletin de Geología**, v. 41, n. 2, p. 35-45, 2019.DOI: /10.18273/revbol.v41n2-2019002
17. FUNNELL, D.; PRICE, M. Mountain geography: A review. **The Geographical Journal**, v. 169, n. 3, p. 183-190, 2003.DOI: 10.1111/1475-4959.00083
18. GARCÍA, C. Trazados de baja y alta sinuosidad en ríos españoles. **Papeles de geografía**, n. 18, p. 9-29, 1992.
19. GÉNOVA, M. et al. Dendrogeomorphological evidence of flood frequency changes and human activities (Portainé Basin, Spanish Pyrenees). **Tree-ring research**, v. 74, n. 2, p. 144-161, 2018. DOI: 10.3959/1536-1098-74.2.144
20. GOERL, R.; KOBIYAMA, M.; SANTOS, I. Hidrogeomorfologia: princípios, conceitos, processos e aplicações. **RevistaBrasileira de Geomorfologia**, v. 13, n. 2, 2012. DOI: 10.20502/rbg.v13i2.166
21. GONZÁLEZ-ÁVILA, I., KOBIYAMA, M., GOERL, R.F., PAIXÃO, M., MENEZES, D. Some considerationsonsociogeomorphology and its importance in integrated management of natural resources. In Simpósio Brasileiro de Recursos Hidricos XXIV- Belo Horizonte, MG, Brazil. 2021.
22. GOODCHILD, M.F.The fractal Brownian processes as a terrain simulation model: Proceedings, Thirteenth Annual Pittsburg Conference on Modeling and Simulation, Pittsburgh, v.13, p. 1133-1137, 1982.
23. HJELMFELT JR, A.Fractals and the river-length catchment-area ratio. **JAWRA - Journal of the American Water Resources Association**, v. 24, n. 2, p. 455-459, 1988. DOI: /10.1111/j.1752-1688.1988.tb03005.x

24. IBAMA - Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis. **Plano de manejo Parque Nacional de Apartados da Serra e Serra Geral**. Brasília. MMA/ IBAMA. Consultado 10/02/2020. 2019. Disponível: https://www.icmbio.gov.br/portal/component/content/article?id=2195:parna-de-aparados-da-serra.
25. LA BARBERA, P., ROSSO, R. Fractal geometry of river networks. **Water Resources Research**, v. 27, n. 3, p. 381-404 387, 1987. DOI: /10.1029/WR025i004p00735
26. LATTMAN, L., and PARIZEK, R. Relationship between fracture traces and the occurrence of groundwater in carbonate rocks. **Journal of Hydrology**, 73-91. 1964. DOI: /10.1016/0022-1694(64)90019-8
27. MANDELBROT, B. B. Stochastic models for the Earth's relief, the shape and the fractal dimension of the coastlines, and the number-area rule for islands. **Proceedings of the National Academy of Sciences**, v. 72, n. 10, p. 3825-3828, 1975.DOI: 10.1073/pnas.72.10.3825
28. MARTÍNEZ, G.; DÍAZ, J. Morfometry in San José del Cabo Hidrologic Basin, South Baja California, México. **Revista Geológica de América Central**, n. 44, p. 83-100, 2011.
29. MAZZALI, L.H.; DIAZ, L.R.; KOBIYAMA, M.; CAMPAGNOLO, K. Aplicação da NBR 15505-2:2019 na Análise dos Trechos da Trilha do Rio do Boi no Parque Nacional de Aparados da Serra, Sul do Brasil. **Biodiversidade Brasileira**, 2021.
30. MONTANARI, A. et al. "PantaRhei—everything flows": change in hydrology and society—the IAHS scientific decade 2013–2022. **Hydrological Sciences Journal**, v. 58, n. 6, p. 1256-1275, 2013.https://doi.org/10.1080/02626667.2013.809088
31. MORENO, J. A. **Clima do Rio Grande do Sul**. Secretaria da Agricultura. Porto Alegre, 1961.
32. MOTA, A.; GRISON, F.; KOBIYAMA, M. Relação entre sinuosidade e índices topográficos na zona topográfica fluvial. **RevistaGeonorte**, v. 4, n. 13, p. 42-60, 2013.ISSN – 2237-1419
33. MUELLER, J. An introduction to the hydraulic and topographic sinuosity indexes. **Annals of the association of american geographers,** v. 58, n. 2, p. 371-385, 1968.DOI:/10.1111/j.1467-8306.1968.tb00650.x
34. OLLERO OJEDA, A. Dinámica de meandros y riesgos hidrogeomorfológicos en Alcalá de Ebro y Cabañas de Ebro (Zaragoza). **Cadernos do Laboratorio Xeoloxico de Laxe**, v.21.1996.
35. PAIXÃO, M. A.; CORSEUIL, C. W; KOBIYAMA, M.; GONZALEZ AVILA, I.; VANELLI, F. M.; OLIVEIRA, H. U.; VASCONCELLOS, S. M.; CAMPAGNOLO K.; FAGUNDES, M. R. Occurrence of multi-disasters in the Mampituba River basin, southern Brazil, during the COVID-19 pandemic. **International Journal of Erosion Control Engineering,** v. 13, n. 4, p. 84-92. 2021. DOI:/10.13101/ijece.13.84
36. PAIXÃO, M.; KOBIYAMA, M. Relevant parameters for characterizing mountain rivers.**Brazilian Journal of Water Resources**, v. 24, p. 1-13, 2019.DOI:/10.1590/2318-0331.241920180115
37. PAIXÃO, M. A. **Hydrogeomorphological characterization of a canyon river in Southern Brazil: a specific type of mountain river**. 2021. 117 f. Tese (Doutorado)-Universidade Federal do Rio Grande do Sul, Instituto de Pesquisas Hidráulicas, Programa de Pós-Graduação em Recursos Hídricos e Saneamento Ambiental, Porto Alegre, BR-RS, 2021.
38. PANDOLFO, C.; BRAGA, H. J.; SILVA JÚNIOR, V. D.; Massignan, A. M.; Pereira, E. S.; THOMÉ, V. M. R.;& VALCI, F. V. **Atlas climatológico do estado de Santa Catarina**. Florianópolis: EPAGRI, 1, 2002.
39. PINTO, R.; PASSOS, E.; CANEPARO, S. Considerações a respeito dos condicionantes utilizados em pesquisas envolvendo movimentos de massa. **Geoingá: Revista do Programa de Pós-Graduação em Geografia (PGE/UEM),** v. 5, n. 1, p. 102-124, 2013.ISSN 2175-862X
40. QAZI, N. et al. Hydrology of the Himalayas. In: **Himalayan Weather and Climate and their Impact on the Environment.**Springer, Cham. p. 419-450, 2020.DOI: 10.1007/978-3-030-29684-1_21
41. RAMÍREZ HERNÁNDEZ, R., RODRÍGUEZ INFANTE, A., & ORDAZ HERNÁNDEZ, A. Dimensión fractal de redes de drenaje controladas estructuralmente en cuencas hidrográficas de Pinar del Río, Cuba. **Minería y Geología**, 33(2), 163-176, 2017.
42. RAMLI, M. F. et al. Lineament mapping and its application in landslide hazard assessment: a review. **Bulletin of engineering Geology and the Environment,** v. 69, n. 2, p. 215-233, 2010.DOI: 10.1007/s10064-009-0255-5
43. RAMOS, A. L. D., **Sistema fluvial do rio jacaraípe, serra, espírito santo: proposta de análise a partir do geossistema e da sociogeomorfologia.** 2018. 232p. DoctoralDissertation- Universidade Federal do Espírito Santo, CCHN - Centro de Ciências Humanas e Naturais, Vitória, ES. Disponível em: <http://repositorio.ufes.br/handle/10/10674 >. Acesso em: 06 abr. 2021.
44. RODRÍGUEZ-ITURBE, I.; RINALDO, A. **Fractal River basins: Chance and self-organization**. Cambridge: Cambridge University Press 547p, 1997.
45. ROSS, J. Relevo brasileiro: uma nova proposta de classificação. **Revista do Departamento de Geografia**, v. 4, p. 25-39, 1985.DOI: https://doi.org/10.7154/RDG.1985.0004.0004
46. ROSSO, R., BACCHI, B., LA BARBERA, P. Fractal relation of mainstream length to catchment area in river networks. **Water Resources Research**, v. 27, n. 3, p. 381–387, 1991. DOI:/10.1029/90WR02404

47. ROTH, G.; LABARBERA, P.; GRECO, M. On the description of the basin effective drainage structure. **Journal of hydrology.** n.187, p. 119-135, 1996.DOI:/10.1016/S0022-1694(96)03090-9
48. SCHEIDEGGER, A. E. Hydrogeomorphology. **Journal of Hydrology**, n. 20, p. 193-215, 1973.DOI: /10.1016/0022-1694(73)90061-9
49. SCHULLER, D. J.; RAO, A. R.; JEONG, G. D. Fractal characteristics of dense stream networks. **Journal of hydrology**, v. 243, n. 1-2, p. 1-16, 2001. DOI: 10.1016/S0022-1694(00)00395-4
50. STRIEDER, A.J.; AMARO V.E. Structural patterns removed from remotely sensed lineaments. **Revista da Escola de Engenharia**- EGATECA, 25 (4):109-117. 1997
51. TARBOTON, D. G. Fractal River networks, Horton's laws and Tokunaga cyclicity. **Journal of Hydrology**, v. 187, n. 452 1-2, p. 105-117, 1996. DOI: /10.1016/S0022-1694(96)03089-2
52. TARBOTON, D.G.; BRAS, R.L.; RODRIGUEZ-ITURBE, I. The fractal nature of river networks. **Water Resources Research**, v.24, n.8, p. 1317-1322, 1988.DOI: https://doi.org/10.1029/WR024i008p01317
53. TAVARES, T. D. G. A., SILVA, D. F., & KOBIYAMA, M. Geometria fractal da bacia hidrográfica do Rio Maquiné/RS. In: XXIISimpósio Brasileiro de Recursos Hídricos, 22, 2017, Florianópolis, **Anais**. Porto Alegre: ABRH, 2017.
54. UNITED NATIONS CONFERENCE ON ENVIRONMENT AND DEVELOPMENT (UNCED), Agenda 21, Div. for Sustain. Dev., U. N. Dep. of Econ. and Soc. Affairs, New York. 1992. Disponível em: http://www.un.org/esa/sustdev/documents/agenda21/english/agenda21toc.htm).
55. US FEDERAL COUNCIL FOR SCIENCE AND TECHNOLOGY(FCST). **Scientific Hydrology Ad Hoc Panel on Hydrology**, Washington, DC. 1962.
56. VASCONCELLOS, S. et al. Flood Hazard Mapping in Alluvial Fans with Computational Modeling. **Water Resources Management**, p. 1-16, 2021.DOI: 10.1007/s11269-021-02794-7
57. VESTENA, L.; KOBIYAMA, M. A geometria fractal da rede de drenagem da bacia hidrográfica do Caeté, Alfredo Wagner-SC. **Revista Árvore**, v. 34, n. 4, p. 661-668, 2010. DOI:/10.1590/S0100-67622010000400010
58. VIVIROLI, D.et al. Mountains of the world, water towers for humanity: Typology, mapping, and global significance. **Water resources research**, v. 43, n. 7, 2007. DOI:/10.1029/2006WR005653
59. VIVIROLI, D.; WEINGARTNER, R. The hydrological significance of mountains: from regional to global scale. Hydrology and earth system sciences, v. 8, n. 6, p. 1017-1030, 2004. DOI: /10.5194/hess-8-1017-2004
60. WANG, S. et al. Research on the Model Improvement of a DLA Fractal River Network. **IEEE Access**, v. 8, p. 100702-100711, 2020. DOI: /10.1109/ACCESS.2020.2997923
61. WEBER, E.; HASENACK, H. (org.). **Base cartográfica digital do Rio Grande do Sul - escala 1:250.000**. Porto Alegre: UFRGS Centro de Ecologia. 2007. 1 CD-ROM. (Série Geoprocessamento n.1). ISBN 85-7727-039-4.
62. WILDNER, W.; ORLANDI FILHO, V.; GIFFONI, L. E. Itaimbezinho e Fortaleza, RS e SC-Magníficos canyons esculpidos nas escarpas Aparados da Serra do planalto vulcânico da Bacia do Paraná. **Sítios Geológicos e Paleontológicos do Brasil**. Publicado na Internet em, v. 1, n. 07, p. 2006, 2006.
63. XU, T.; MOORE, I.; GALLANT, J. Fractals, fractal dimensions and landscapes—a review. **Geomorphology**, v. 8, n. 4, p. 245-262, 1993.
64. ZHANG, L. et al. How canyons evolve by incision into bedrock: Rainbow Canyon, Death Valley National Park, United States. **Proceedings of the National Academy of Sciences**, v. 117, n. 26, p. 14730-14737, 2020. DOI:/10.1073/pnas.1911040117
65. ZWOLIŃSKI, Z.; GUDOWICZ, J. Geomorphometric analysis of morphoclimatic zones on the Earth. methods, v. 4, n. 5, p. 12, 2015