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Artigo de Pesquisa

Asymmetry Factor application based on the sectorization of watersheds: Morphostructural analysis of the Chopim River catchment, Paraná State (Brazil)

Aplicação do Fator de Assimetria baseado na setorização de bacias hidrográficas: Análise morfoestrutural da bacia do Rio Chopim, Paraná (Brasil)

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Abstract: The watershed asymmetry factor is a morphometric index used to search structural influence in the landscape. However, this toll is subjected to the camouflage effect, when some features could be omitted because of its size, age or dissection's state. The watershed sectorization was developed to introduce a new concept that refine the applying the asymmetry factor. Compartmentalize the catchment in sectors using geological and/or geomorphic patterns contributes to the structural impact of relief becoming better dimensioned, in the same way allowing the compartmentation of any data analyzed in the watershed. The Chopim River (southern Paraná) lies between some important fault zones and have none lithological abrupt variation or relevant climatic changes, thereat it was selected to apply the new method. The watershed sectorization was fundamental to recognize the influence of Taxaquara fault in the Chopim catchment threw light in the relation in Taxaquara and other fault zones in the watershed development.

Keywords: Morphotectonic; Asymmetry Factor; Drainage Network; Chopim River; Taxaquara Fault.

Resumo: Dentre os índices morfométricos utilizados nos estudos morfotectônicos se destacam os fatores de assimetria das bacias hidrográficas, entretanto, esse método também está sujeito a imprecisões, como por exemplo a ocorrência do efeito de camuflagem, que ocorre quando feições morfotectonicamente importantes são omitidas devida ao seu porte, idade ou estado de dissecação. A segmentação da bacia hidrográfica em setores visa aprimorar a aplicação dos fatores de assimetria e diminuir o efeito de camuflagem. Os setores são separados segundos características locais do relevo e da rede de drenagem, consistindo em áreas menores, dispostas alinhadas segundo o eixo maior da bacia. A grande vantagem da setorização das bacias em relação aos outros métodos que medem a variação de assimetria, como o Fator de Simetria Transverso e o Gráfico de variação de Assimetria, é a possibilidade de atrelar qualquer dado morfométrico e/ou estrutural aos setores definidos, dessa maneira, o impacto da atuação de estruturas geológicas pode ser mais bem dimensionado. O método aqui estabelecido foi aplicado na bacia do rio Chopim (PR) por sua posição entre grandes zonas de falha da Bacia Sedimentar do Paraná e não apresentar variações expressivas em seu clima ou litotipos. A aplicação dos setores de assimetria permitiu o reconhecimento da influência da zona de Falha Taxaquara no relevo local, o que não tinha sido feito em nenhum dos trabalhos morfotectônicos realizados em escala regional.

Palavras-chave: Morfotectônica; Fatores de Assimetria; Rede de Drenagem; Rio Chopim; Falha Taxaquara.

1. Introduction

Drainage network analysis is one of the most important tools of tectonic geomorphology, largely due to the great susceptibility that the watercourses present to any variation of the stress regime (Schumm, 1986). According to Hack (1960), tectonic stresses cause deformations in the relief, as well as anomalies and asymmetries in the drainage networks, which tend to be attenuated due to the action of weathering and erosive agent's over geological time. Among these, the importance of surface and subsurface drainage in exogenous processes stands out, both as catalysts of chemical weathering processes and as agents of sediment transport. Rivers play a complex role in the evolution of the relief, because while they act in a passive way by molding themselves according to the geological structures of the substratum, submitting themselves to the tectonic forces, they act actively in the denudation and flattening of the relief (Burbank and Anderson, 2011). In contrast, drainage anomalies, such as watershed asymmetry, are important indications of the action of tectonic forces. Although tectonic action is not the only phenomenon responsible for the formation of anomalies in the drainage network, their presence can be considered a good indication of the presence of active or non-active geological structures (Whipple and Tucker, 1999; Wobus et al., 2006).

The evolution of a hydrographic basin occurs by the branching of its main channel, causing it to widen in this process, eroding its original interfluves and incorporating portions of neighboring catchment. This causes the arrangement of the drainage networks and the boundaries of the watersheds to remain in constant change. From this premise, it follows that the catchment originate with elongated shapes and gradually become wider during their evolution, a concept that Bull (1991) uses in determining the elongation index, used in hydrographic analysis, among them in determining watershed symmetry.

Watersheds can be deformed by tectonic events concomitant with their evolution, which generally causes the asymmetry of the edges in relation to the alignment of the slope. On the other hand, the process of lateral expansion of the watersheds, through erosion of their interfluves and adjacent catchment (back-wearing) causes the asymmetries of the watersheds to attenuate over time, which again leads to the close relationship between them and the action of tectonic forces (Penck, 1953). Unlike the elongation index, the watershed asymmetry factor provides more information than just their relative chronology, because the action of stresses can deform already stabilized watersheds, causing anomalies and asymmetries along their course (Keller and Pinter, 1996).

The main methods for obtaining asymmetry used in the literature are the "Asymmetry Factor - AF" (Hare and Gardner, 1985) and the "Transverse Symmetry Factor - T" (Cox, 1994). These methods have been used successfully, obtaining consistent results especially when used together (Salamuni et al., 2003 e 2020; Peyerl et al., 2018). However, both methods have particularities that can provide partial data, in case of inaccuracy in their use. The Asymmetry Factor (AF) considers the total area of the watershed, so if the watershed in question has a long segment with low asymmetry, it can camouflage the asymmetry that exists locally in shorter stretches, as is the case of the Jordão's catchment, located in the state of Paraná, southern Brazil (Peyerl et al., 2018). Aiming to circumvent this problem verified in the AF determination method, the authors used the Transverse Symmetry Factor (T) at the confluence points of the main river of the watershed with its major tributaries, thus making it possible to determine an increasing asymmetry towards downstream.

However, since the Cox method (T) is measured from the distance between medial lines in the watershed and not in its entirety, to obtain good results it is necessary that the Transverse Symmetry Factor be calculated at multiple points along the river. The goal is to build a graph of asymmetry variation (AVG), so it is necessary to draw a large number of auxiliary lines (Peyerl, 2016). It is common for channels to have a meandering course as a result of an arched perimeter of the watershed. Sometimes tracing these lines becomes a relatively complex and time-consuming task, since any error of a few tenths of a degree in the tracing generates results far from the real one.

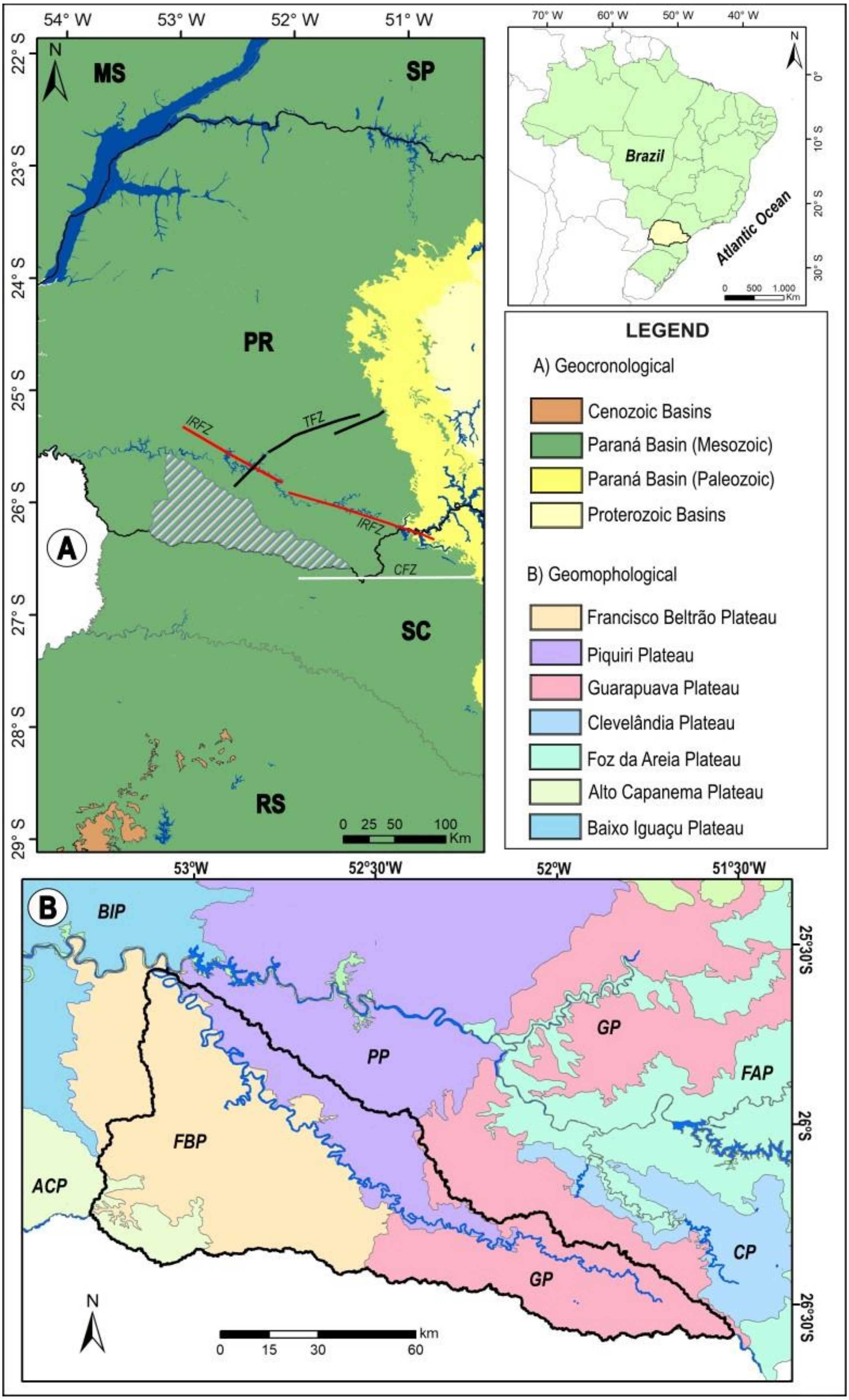

Figure 1. A) Location of the Chopim catchment in the Paraná Sedimentary Basin: IRFZ, Iguaçu River Falut zone (red); TFZ, Taxaquara Fault zone (black); CFZ, Caçador Fault zone (white). B) Geomorphological map of Paraná (MINEROPAR, 2006). The lowest figure in black is the Chopim River catchment.

The proposal of the present paper is to advance in the improvement of the use of methods for determining watershed asymmetry, proposing a routine for the segmentation of drainage networks that can be used in works of tectonic geomorphology. Therefore, hierarchical criteria were established for the compartmentalization of watersheds into multiple segments, aiming at the best application of the T factor (Cox, 1994), due to the perspective of variation along the river course that this method offers. The routine proposed here also allows good integration of the analysis of the symmetry variation in relation to the other data obtained, both via remote sensing and from morphostructural and tectonic cartography.

The development of this routine is based on the subdivision of the watershed according to morphometric criteria, mainly those that consider the properties of the drainage networks, the shape of the longitudinal profiles and the value of the hydraulic gradient. The processing of the images that were used in this routine can be entirely developed in ArcMap©. To exemplify how the process works, we used as an example the Chopim River catchment (Figure 1), tributary of the Iguaçu River and located in the State of Paraná, southern Brazil. The choice is due to uniform lithologic and climatic constitution of the Chopim catchment, where the structural deformation is the major morphogenic agent.

2. Geomorphological and Geological framework of the Chopim River catchment

Paraná State had its five main regional geomorphological units defined by Maack (1947) which from East to West are 1) the Coastal Plain, 2) Serra do Mar, 3) Curitiba Plateau (First Plateau), 4) Campos Gerais Plateau (Second Plateau) and 5) Basaltic Plateau (Third Plateau). The Third Plateau of Paraná, the largest regional geomorphological unit, extends from the Esperança scarp, in the boundary with Second Plateau, to the Paraná River in the far west of the State. The geomorphological mapping of Santos et al. (2006) compartmentalized these units into 50 morphosculptural subunits. The Chopim catchment lies predominantly within four of these subunits, all of which are within the Third Plateau of Paraná: the Palmas/Guarapuava plateau, in the region of its upper course, and in the lower course the plateaus of the High/Middle Piquiri (on the right bank) and the Francisco Beltrão plateau (on the left bank). A small portion of the watershed, in the headwaters of the Marrecas catchment - the largest affluent of the Chopim, located on its left bank - lies a fourth unit, on a higher surface than the Francisco Beltrão plateau, the Alto Capanema plateau (Figure 1).

The Chopim River is an affluent of the left bank of the Iguaçu River and its second largest affluent - the largest one in the Paraná Third Plateau - with a length of about 3900 km and a watershed area of 7470 km^2. Its main course flows from SE to NW (azimuth approximately 45°), but when located on the Palmas/Guarapuava plateau, it has a slightly different direction, flowing from ESE to WNW. The watershed has strong asymmetry (Xavier, 2015), having the most elongated drainages on its left bank, i.e., in the southwestern portion.

Regardless of the geomorphological sub-unit drained, the predominant lithotypes in the basin do not differ. Throughout the basin area, basalts of the Paraná Igneous Province (Peate, 1988), the largest LIP (Large Igneous Province) on the South American continent, formed in the context of the break-up of the Gondwana supercontinent during the Late Cretaceous (South Atlantic Event, Schobbenhaus et al., 1984), are outcropping. These rocks were extravasated in a relatively short time, about 1.2 Ma and have ages – defined by 40Ar/39Ar – around 134±1 Ma (Thiede and Vasconcelos 2008, 2010). As well as the lithologic units, the climatic conditions do not change in that portion of the Third Plateau, configured by a subtropical climate (Alvares et al., 2014) with high relative humidity (>80%) and lowest temperatures in the state (average temperature between 21^{o} and 27^{o}) (IAPAR, 2019).

Even though the geology of the Chopim catchment is relatively uniform, its location near three major fault zones introduces significant structural complexity (Zalán et al., 1986). To the northeast is the Iguaçu River Fault Zone (IRFZ) and to the south is the Caçador Fault Zone (CFZ). The IRFZ is roughly N45W, subparallel to the Ponta Grossa Arch, while the CFZ is E-W. The Taxaquara Fault Zone (TFZ), the third fault zone, has azimuth approximately N50E and according to the original Zalán et al. (1986) layout ends close to the northeast boundary of the Chopim catchment, but latter prolonged into its interior by studies caried by Peyerl et al. (2018) in the Jordan River, located in the other bank of the Iguaçu River.

3. Materials and Methods

The morphotectonic analysis of the Chopim River was carried out by means of remote sensing in ArcMap environment. The analyzed images come from the Topodata Digital Elevation Models (Valeriano and Albuquerque 2010; Valeriano and Rossetti 2012), with 30m resolution, which in turn were reprocessed from Shuttle Radar Topography Mission (SRTM) images with 90 m resolution (National Geospatial-Intelligence Agency - NGA; U.S. National Aeronautics and Space Administration NASA). In the next topics (3.1-3.3) will be described how they imageries were extracted and shapes were delineated.

3.1 RDE/RDT and Knickpoints Density Map

The Hydrology, Spatial Analyst and 3D Analyst tools were used, in addition to the KnickpointFinder (Queiroz et al., 2015). Using the KnickpointFinder tool, the drainage network of the Chopim River and its knickpoints were extracted with their RDE index (slope-extension ratio), normalized by the RDE/RDT index. The shapefile generated by this tool display the knickpoints in points and not in knickzones attached to drainage network, the main method in knickpoints analyzes (Kirby and Whpple, 2012). To be best interpretated, this points shapefile could be statistically treated either by the its concentration or by its dimension.

To accomplish the knickpoints concentration were used the kernel density tool from the SpatialAnalyst Tools package, which aggregate the knickpoint location in poles and gives rise to the knickpoint density map (KDM), developed by Queiroz et al. (2015) and Peyerl et al. (2017) and used in the delineation of geological layers and structural zones. The cores were defined in km², using the tool's default configuration ranges, automatically calculated using the watershed's dimension. The Kernel Density tool uses the Silverman (1992) function to determine the grid intervals, based in imputed values distribution. In the KDM the tools use the knickpoints RDE/RDT values and the geographic distributions to determine the measurement grid.

The indexes RDE, RDT and RDE/RDT were proposed by Etchebehere et al. (2004) and are based - like the slope index - on the normalization of the hydraulic gradient (SL) of Hack (1973), so that the values are adjusted according to their position along the watershed. The RDE index is given by the expression $RDE = L*\Delta h/\Delta l$, where L represents the watershed length. RDT in turn equals the slope of the sub-basin in which the knickpoint is located, given by the equation $RDT = (\Delta h / L)*\ln(L)$. The ratio between them (RDE/RDT) is the value assigned to the knickpoint and used in all subsequent analyses. RDE/RDT was developed by Etchbehere et al. (2004) based on Seeber and Gornitz's (1983) proposal in defining 1st and 2nd order knickpoints, who used the SL/SLT index, where SL is Hack's index and SLT is the hydraulic gradient applied for the entire watershed. The authors then determined the value of 10 as the limit between the 1st and 2nd order knickpoints, a boundary also used by Etchebehere et al. (2004) for the RDE/RDT. Later, in the same vein, Peyerl et al. (2023) proposed the RDE/RDT Ranks, increasing the number of knickpoint intervals from 2 to 5, and correlating them with their respective waterfalls in the field. The Rank 1, with values lower than 10, embrace knickpoints with minimal impact in the profile to the point the higher Ranks presents measurable unevenness (Peyerl et al., 2023), since centimetric (Rank 2) to decametric (Ranks 5).

3.2 Lineaments

The Azimuthfinder tool (Queiroz et al., 2014) was used to obtain the directions of the lineaments plotted on the images used. The lineaments were divided into two groups, the relief lineaments, drawn on the shaded relief images (Hillshade - Spatial Analyst Tools) and those drawn on the 1st and 2nd order drainages (Strahler; 1957). While there are similarities between these two types of lineaments, the relief lineations and lineaments tend to reveal the major structures that shape the evolution of the relief, in a macro-scale analysis, while the drainage lineations are based on younger and often incipient stresses.

3.3 Asymmetry Factor

The Asymmetry Factor (AF) of Hare and Gardner (1985) (Figure 2) is the most widespread of the methods for measuring watershed asymmetry, due to its simple calculation, based on the relationship between the watershed margins, which are usually already delimited from Digital Elevation Models (DEM) along with their respective areas. The Asymmetry Factor is obtained by the following equation:

$$FA = 100 \text{ x } Ad/At \text{ [where Ad=right area; At=total area].}$$

As a criterion for quantitative asymmetry classification, the three intervals proposed by Keller and Pinter (1996) were used, which are, respectively, (a) low asymmetry, FA values between 40 and 60, meaning that the right margin is equivalent to almost half of the total; (b) moderate asymmetry, when FA is greater than 30 and less than 40 or, still, when FA is greater than 60 and less than 70; (c) strong asymmetry, for values less than 30 or greater than 70.

The Cox (1994) Transverse Symmetry Factor (TSSF or T) (Figure 2) is based on the distance between the midline of the watershed (bisector), its interfluve and its main channel. It is done by drawing lines oblique to the main river, from which the distances necessary to calculate T are obtained, which is defined by:

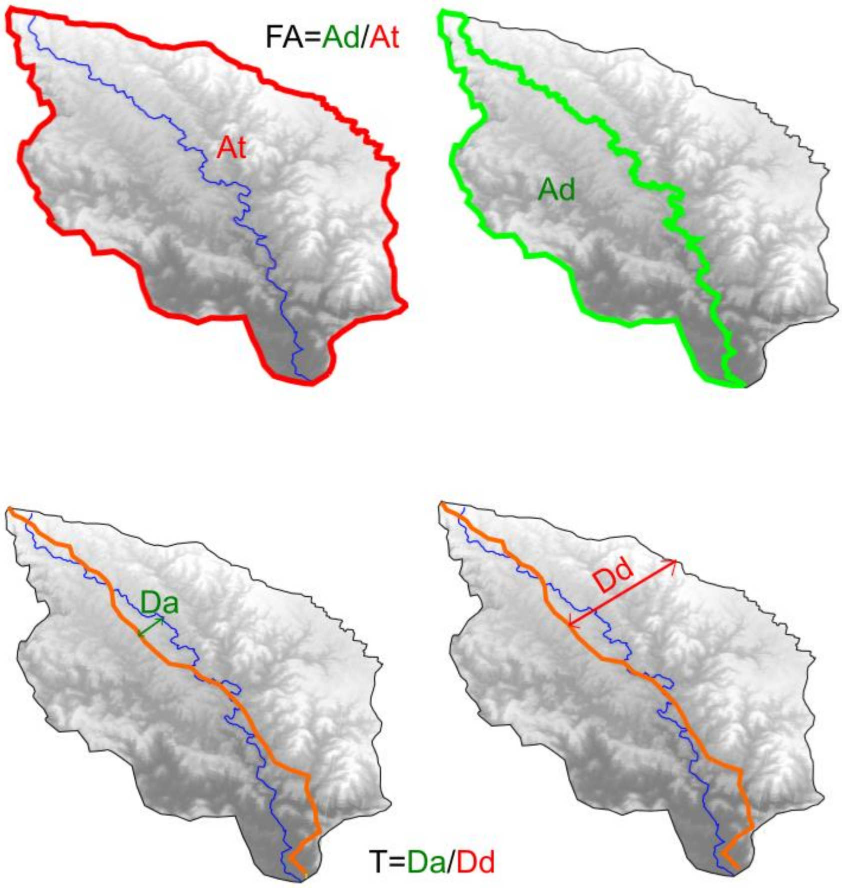

Figure 2. Illustration exemplifying the asymmetry factors. The upper pair of figures represents Hare and Gardner's (1985) Asymmetry Factor (AF), and the lower one represents Cox's (1994) Transverse Symmetry Factor (T). The orange line in the lower figures represents the midline of the watershed.

$$T = Da/Dd$$

[Both values are obtained by the tracing of lines across the river, where each value of Da=distance between the points where this line crosses the river and the midline of the watershed, and Dd=distance between the interfluve and the midline of the watershed cut by this same line.]

The asymmetry intervals that are used in the analysis of T values were also defined by Keller and Pinter (1996), who defined as (a) low asymmetry values those less than 0.2; (b) moderate asymmetry between 0.2 and 0.5; and (c) strong asymmetry those greater than 0.5.

3.4 Sectoring of the morphostructural data

Although the application of sectoring allows the observation of the marked asymmetry variation throughout the watershed, this would also be possible by using the asymmetry variation graph (AVG, Figure 3). The sectorization method, however, allows the analysis to be extended beyond the asymmetry variation of this point due to the compartmentalization of the other morphometric data (detailed in the next chapter, 4).

The compartmentalization of the watershed in sectors allows the division of the other data according to these same parameters, which helps in the contextualization and zoning of the directional patterns. To exemplify the routine efficiency have been chosen four morphometric methods, that were analyzed under the focus of sectorization, 1) Major relief lineaments (Figure 7), 2) Direction of 1st and 2nd order drainages (Figure 8), 3) Knickpoints concentration, using the knickpoint density map (KDM, Figure 9), 4) Slope map (Figure 10).

1) Relief lineaments configures one of the more commons methods to correlate structural influence in the landscape and that method were chosen to shows how the basin's segmentation change the patterns along the catchment.

2) The importance of lower order drainage is due to the greater susceptibility of the drainage network to variations in tectonic stresses (Schumm 1986), and it is possible to conclude that the 1st order drainages will be the first response to variations in the morphotectonics (Salamuni, 1999). Therefore, their orientation patterns are related to tectonic efforts to which the watershed is submitted or has been submitted in a recent time interval, with no time for them to be remodeled by erosive processes.

3) KDM is used to show the knickpoints alignment through different subbasins (Peyerl et., 2017 and 2018) at the same time that evidence the more instable portions of the area. Segmentate the KDM were used to correlate the concentration patterns and changes in asymmetry.

4) The slope map is one of the most reliable imageries provided by remote sensing that highlights changes in the relief declivity, what usually configures some important geomorphologic asset, like lithologic changes and geological structures. Observe the slope map from the sectors compartmentation is important to compare how the slope patterns behave compared to other features.

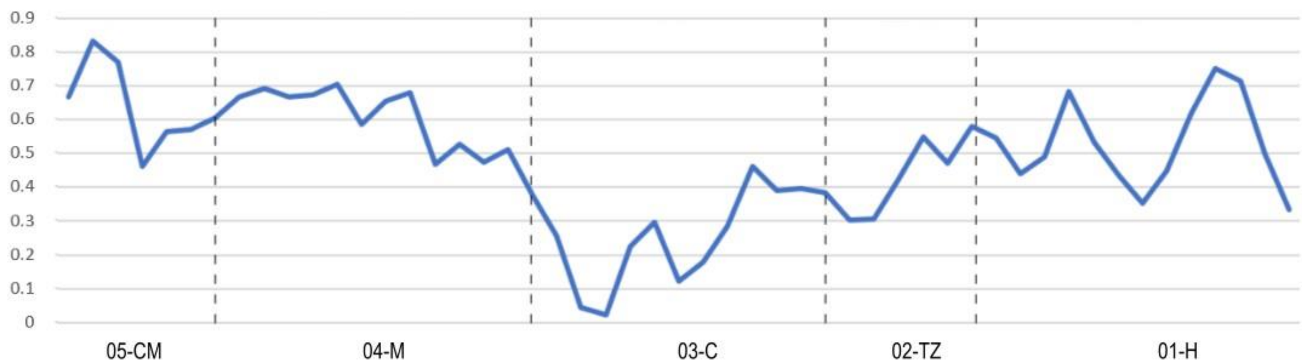

Figure 3. Chopim River Asymmetry Variation Graph, made by dividing it into 51 equidistant transversal lines.

4. "Sector" division method

The Transverse Symmetry Factor (T) is often used for the purpose of looking at variation in asymmetry across the watershed, as was done by Peyerl et al. (2016), who calculated T at 8 points along the Jordão River course. While the T-factor has the advantage that it can be used in this way, its resolution depends on the number of times it is applied throughout the watershed. When arranged in an XY diagram, that line configure the Asymmetry Variation Graph (AVG), where X is the watershed length and Y is the variation of the T-factor, However, as already mentioned, the accuracy of this graph depends on the quantity of transversal lines, otherwise it can lead to the same problem as the application of AF, that is, in the camouflage of morphologically important sectors.

The method that we will explain and apply in this work - watershed sectoring for asymmetry analysis - has the purpose of obtaining the same gains as AVG, but with the application of AF instead of T, because AF can be obtained in a much simpler and safer way, since river sinuosities can result in transversal lines with wrong angles, which can cause significant discrepancies in the values of T. This change makes the AVG much more accurate.

Sectoring can be performed according to several parameters, such as the definition of sectors of equal length, but the most appropriate is that this division is performed by hydrographic and/or morphometric requirements. In this way the established sectors will also be determined by other morphometric factors, so that the multiple data sources of this nature can be analyzed in an integrated way. This makes drainage network analysis essential for the construction of the asymmetry sectors. Therefore, the definition of patterns, anomalies and variations in the drainages become the first factors in the definition of the sectors. The concepts of Howard (1967) and Soares and Fiori (1976) were used to accomplish this task, especially those related to drainage patterns, anomalies, asymmetry and density.

Although the watershed's morphometric features can be used to divide it into sectors, the main factor to be used for this purpose is the base level, which is one of the key factors in the evolution of drainage networks and relief. Medium to large hydrographic basins generally have more than one base level, so that the evolution of the portions controlled by each of these levels occurs independently (according to the principles established by Penck, 1953; King 1953; Gardner, 1983). Taking into account the importance of the base levels, they should be used as the first requirement in the subdivision of the basins. This criterion was used by Peyerl et al. (2018) in the subdivision of the Jordão catchment into two zones, the upper and lower Jordão River, where the catchment's base level is dominated by the Pinhão River, the main affluent of the Jordão River.

The application of the sectors - as well as AVG - requires a sufficient number of sectors to be defined so that the variation in symmetry and other factors can be observed, and it is in this context that the other features, pattern variations, and drainage anomalies will be employed. The first routine's step is marking important changes in the catchment and/or the trunk river like lithologic changes, different morphostructures, drainage anomalies or changes in the base level (Figure 4). Then in these points are traced lines orthogonal to the river, dividing the watershed in the symmetry sectors.

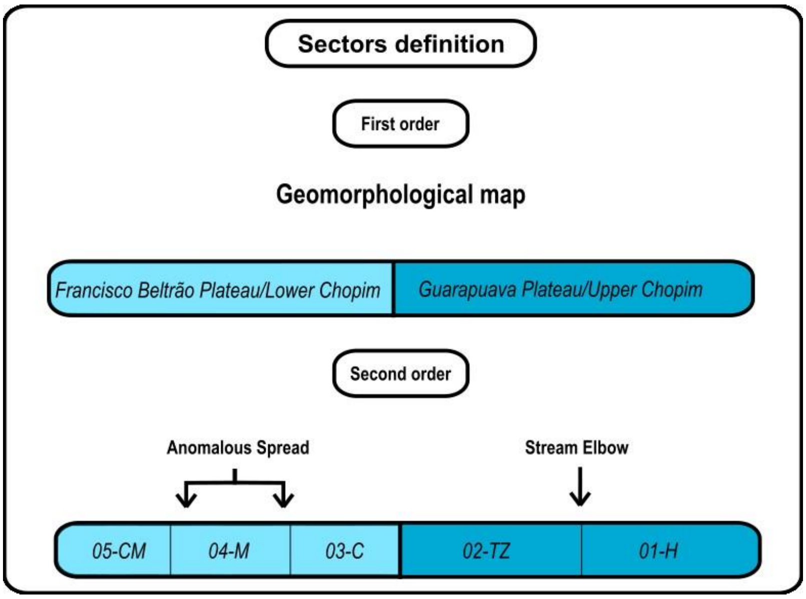

Figure 4. Criteria used to segmented the Chopim catchment in sectors.

Each of the sectors will be composed of two domains, separated from each other by the catchment's main drainage, i.e., one of the domains will be located on the right bank and the other on the left bank of the river. The dividing lines between the sectors are delimited by relief features, such as interfluves of their sub-basins, but they should be as parallel as possible, making the two domains of the same sector similar in length. There is not an exact number of sectors/domains that will be determined in each watershed, but the number of defined sectors must be sufficient to detect variations in the morphostructural indicators, thus, the more sectors are differentiated, the better the result from future analyses. The term "symmetry domains" is based on the concept of domain from the interpretation method of Soares and Fiori (1976), which would be configured by regions with morphological characteristics, drainage patterns and relief that make these domains different from adjacent terrains.

Although the sectors cover both margins of a watershed segment, their compartmentalization is focused on the variations between the domains, thus seeking to isolate the heterogeneous regions of the watershed. Therefore, it is not expected that the two banks of a sector will be texturally homologous to each other in the image, as they will configure a pair only for the purpose of asymmetry analysis.

4.1 Delimitation of the sectors

The Chopim River partially drains four morphoscultural sub-units of the State of Paraná (Figure 1), constituted by the Palmas/Guarapuava Plateau (GP) - region that extends from its headwaters to approximately one third of its course -, the High/Middle Piquiri Plateau (PP), the Francisco Beltrão Plateau (FBP) and a small portion of the Alto Capanema Plateau (ACP). The Chopim River shows different drainage patterns in GP and the other morphoscultures, divided by a evident knickzone (Figure 5). At GP, the Chopim River flows WNW and then – in lower course – flows NW, which determines the previous division of the Chopim catchment into two large zones (Figure 4), which in turn were subdivided according to variations in the longitudinal profile and drainage patterns.

These relief breaks were correlated to other characteristics of the Chopim drainage network, as well as to its drainage anomalies, from which five sectors were defined (Figure 6), totaling in all ten domains, named according to their positions and characteristics. During the analyses each of the domains was referred to by an acronym, preceded by the sector number (from 01 to 05, in relation to the upstream) and at the end the letters R (right) or L (left), to position the block in relation to the Chopim River (Table 1). The abbreviations for each block are: H, Chopim Headwaters sector (01); TZ, Transition Zone sector (02); C, Central sector (03); M: Marrecas Sector (04); CM: Chopim’s Mouth sector (05); for example, the 04-MSL, is the domain where the Marrecas River is located. The choice of domain names was made in order to facilitate their reading and recognition by their acronyms throughout the text (Table 1).

Table 1. Table with asymmetries sector acronyms.

Sector	01-H	02-TZ	03-C	04-M	05-CM
Domain	01-HR	02-TZR	03-CR	04-MR	05-CMR
	01-HL	02-TZL	03-CL	04-ML	05-CML

The knickzone in the limit of GP were named transition zone, and is marked by a convex form in longitudinal profile (Figure 5). That zone divides the upper Chopim in two sectors, named headwaters (01-H) and Tranzition Zone (02-TZ). 01-H is marked by the asymmetry of tropy between its two domains. The Chopim affluent rivers in the right domain (HR) have a predominance of a single direction of flow difference (WSW), while those in the left (HL) flow in NNW, NW, and WNW directions. This tropy variation is much smoother in the other sector of the upper Chopim River, 02-TZ. The 02-TZ is marked by a smaller discrepancy between the areas of the left and right domains, however, unlike the 01-H - and also the other sectors - it presents asymmetry between the density of channels, the left domain (TZL) being much more branched. The boundary between the 02-TZ and the 01-H is marked by a drainage anomaly, where the main channel of the Chopim fits into a stretch of NE-SW direction, culminating in the greatest symmetry between the domains of this portion of the watershed. At the end of this NE stretch Chopim forms an elbow and flows again in the WNW direction.

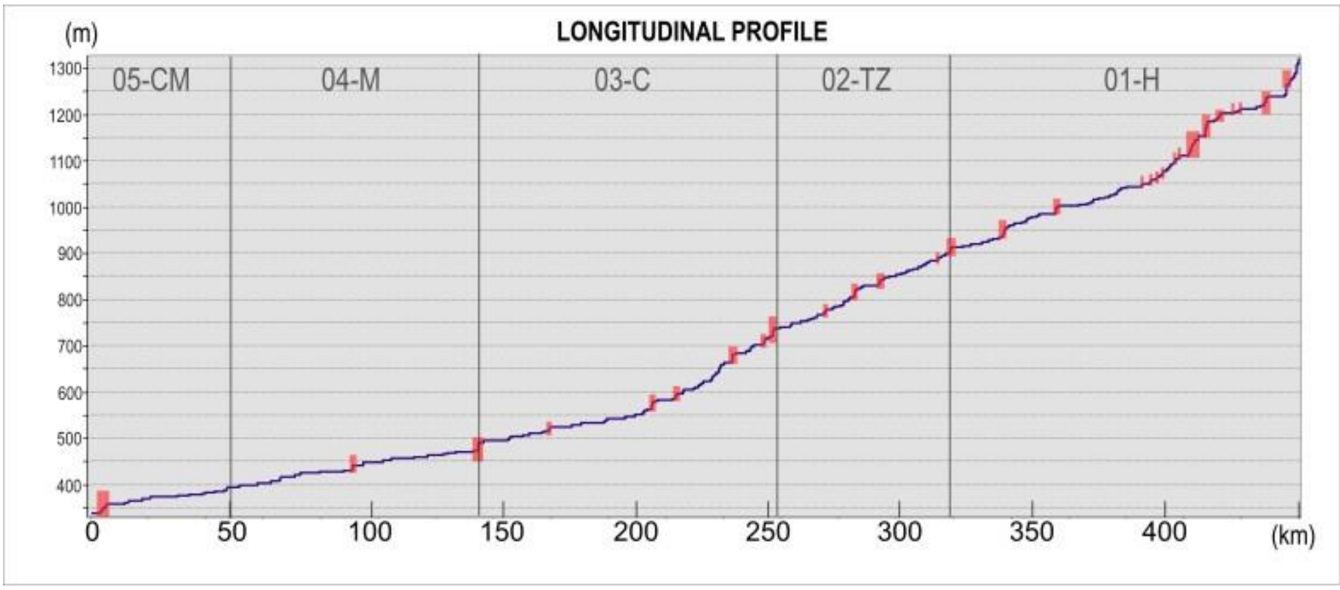

Figure 5. Longitudinal profile of the Chopim River with its 5 delimited sectors. Small red rectangles marc knickpoints in the profile.

Moving into the region of the lower Chopim River, the third sector was delimited, called 03-C (Central sector, Figure 6). These domains have a dendritic/subdentritic drainage pattern and are marked not only by the decrease of the watershed asymmetry, but also by the change of the directional pattern of the drainages of the left domain, which flows with preferential direction towards NNW to N. This variation marks a difference of tropy between the domains of the right (03-CR) and left (03-CL) margins. On the right margin the drainages have only one preferential direction (southwest), differently from the left margin where the greatest concentration of them flow to two directions, NNW and N, as well as having a smaller number of drainages flowing in the NNE and NE directions, as well as the Marrecas sector (04-M) and some segments of NW-SE direction, near the southern limit of the watershed. Although in a more tenuous way, this tropy variation can also be observed in the following sector: 04-M.

The most evident of the sectors is the 04-M and is configured by the drainage network of the largest affluents of the Chopim River; the Marrecas River, the Santana River and the Vitorino River, both in the left domain of the 04-M, which configures the largest of the 10 domains defined in the Chopim catchment. The drainage pattern is similar in the two domains, both with a predominance of drainages in a dendritic pattern, with the largest channels flowing preferentially to the northeast (left domain) or southwest (right domain). What marks this segment is a significant increase in the area of the left bank of the Chopim, without any marked change in its course, nor in the area of its right domain.

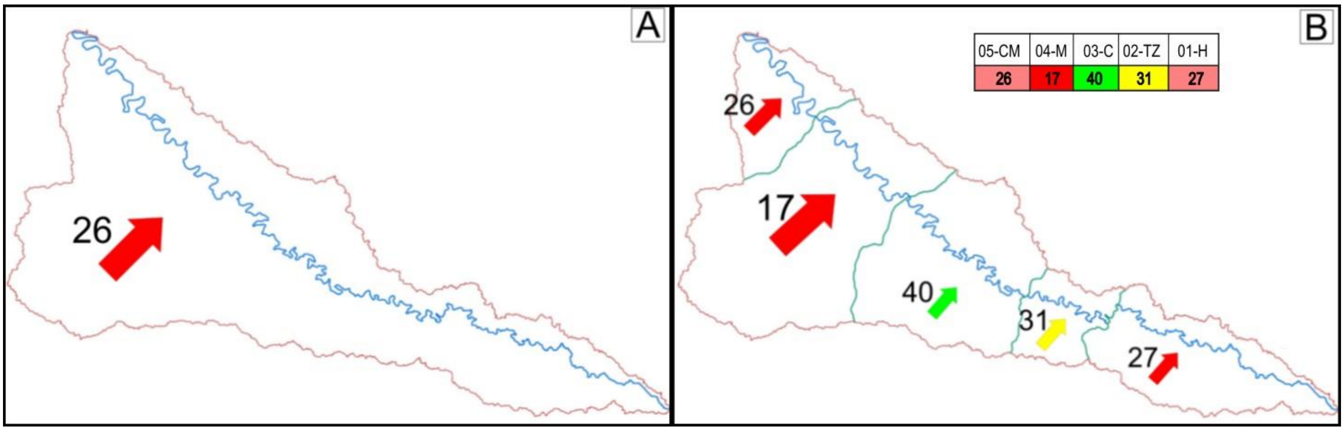

Figure 6. Delimitation of the sectors with their asymmetry factor (AF) values. Figure A shows the value for the entire watershed and B shows the variation that occurs in asymmetry along the sectors.

The most downstream portion of the Chopim catchment configures the sector 05-CM marked by the tapering that the watershed presents in this stretch. In terms of drainage patterns, its two domains have drainage predominantly with dendritic/subdendritic geometry and with the same direction as preferential fluvial flows of 04-M.

4.2 Asymmetry values

The application of the Asymmetry Factor (AF - Hare and Gardner, 1985) in each of the 5 sectors reveals the variation of asymmetry along the watershed, which can be observed in Figure 6 and Table 2. The Chopim River has FA of 26, a value similar to sectors 01-H and 05-CM, but with important variations in the intermediate sectors. Sector 03-C has a smoother asymmetry (36), a change that starts to occur already in sector 02-TZ. The most striking variation occurs in the sector 04-M, which has a value of 17, due to the addition of the area of sector 04-ML.

Table 2. Asymmetry Factor Values of the Chopin River (AF) and its 5 sectors.

Sector	Chopim	01-H	02-TZ	03-C	04-M	05-CM
FA	26	27	31	40	17	26

4.3 The Individualization of the sectors

4.3.1 Chopim Headwaters Sector (01-H)

The first segment of the Chopim catchment (Figure 6) has high asymmetry, with an AF value of 27, close to the watershed's AF value of 26. Both the right and left domains have a strong directional trend of lineaments to the E-W. The predominant direction of structural lineaments in both cases is E-W, with the 01-HR having secondary directions to ENE-WSW and to WNW-ESE and the 01-HL having secondary directions to N-S, NNW-SSE and NW-SE (Figure 7).

The first-order drainages also have similar directions in both compartments, with a preference for the E-W direction, as do the structural lineaments. Drainages oriented in the NE-SW, ENE-WSW, WNW-ESE and NW-SE directions are also frequent, with the lowest density of drainages being marked for NNW-SSE, N-S and NNE-SSW (Figure 8).

The slope in the two domains is similar, being predominantly composed by a slightly undulating region with some drainages with intermediate slope valleys. The exceptions to this pattern are the median portion of the 01-HR, where some drainage segments with higher slope values occur, as well as in the portion near the boundary with sector 02-TZ.

Although this is the segment with the lowest concentration of knickpoints - as well as the lowest occurrence of large knickpoints - the domains of 01-H still show influence of these features. At 01-HR the knickpoint density map (Figure 9) reveals a trend of points with a WNW direction, parallel to the course of the Chopim River in this section. The 01-HL shows a low density of knickpoints, the lowest among all ten domains, but presents three relevant lineations of these features, although not as marked as the trend of the 01-HR. Two of these trends have NE-SW direction, one of them overlapping the anomalous stretch of the Chopim, which occurs on the boundary between it and the 02- TZR. The third trend has E-W direction, is the most tenuous and longest, parallel to the southern limit of the watershed.

4.3.2 Transition Zone Sector (02-TZ)

This segment is on the western edge of the Palmas/Guarapuava plateau and its FA is 31, indicating less asymmetry of the basin in this section than in relation to 01-H. Sector 02-TZ (Figure 6) is the smallest subdivision of the Chopim catchment and also the narrowest. In both domains the first-order drainage directions become less dispersed, concentrating NW-SE in 02-TZR and NE-SW and WNW-ESE in 02-TZL. At 02-TZR the secondary directions are E-W, NNE-SSW and NE-NW, while at 02-TZL they are NNW-SSE and E-W. The domains show distinct patterns regarding lineament directions (Figure 8). In 02-TZR the strongest direction is NW-SE and NE-SW, followed by ENE-WSW and NNE-SSW, but in 02-ZTE the preferential direction is NNW-SSE, followed by NW-SE and E-W.

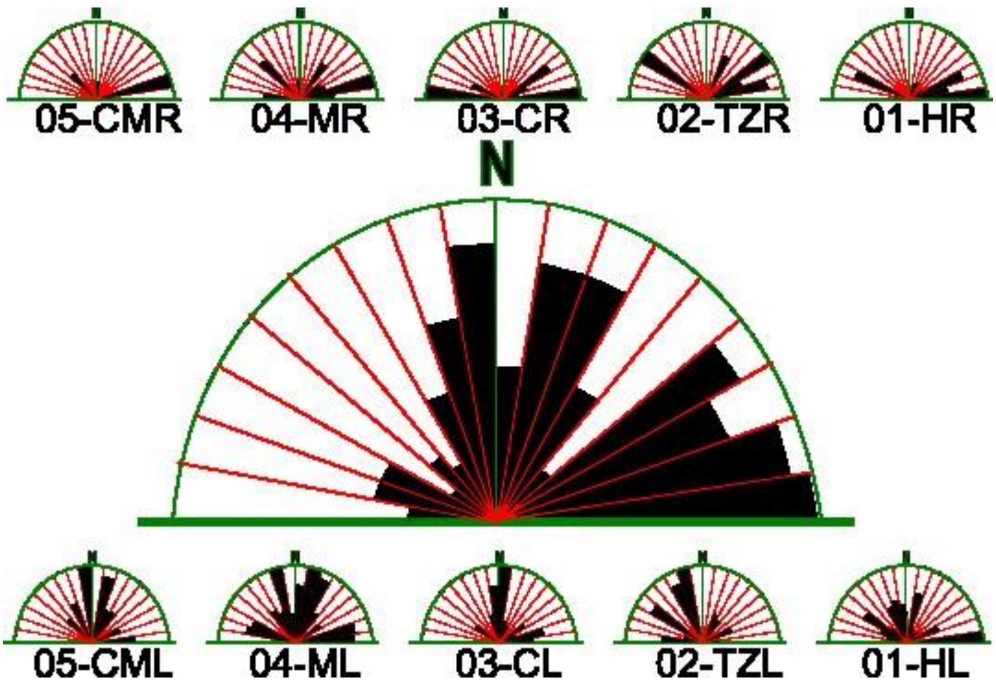

Figure 7. Relief lineaments rosette. Central rosette uses the data for the entire catchment and the smaller ten for each of the domains.

Most of the watershed presents a flattened relief, except for the portion near the Chopim River, where its valley and some other surrounding channels have steeper slopes. In these channels there are some medium-sized knickpoints, with two that deserve to be highlighted due to their larger size. These two knickpoints occur in the same channel, with a distance of a few kilometers between them. The largest of them occurs at the confluence of the channel with the Chopim River and configures the largest waterfall of the upper Chopim (i.e., sectors 01-H and 02-TZ) and its occurrence coincides with the increase in the slope of the Chopim River, which was relatively stable until that point.

The larger knickpoints belong to a point density whose NW-SE direction extends to the boundary with sector 03-C (Figure 9). The main point direction appears to overlap with another, also quite striking, WNW-ESE (E-W) direction. In domain 02-TZL there are two Knickpoints density trends, with NNW-SSE direction, which extend from the southern boundary of the watershed to the highest density zone.

4.3.3 Central Region Sector (03-C)

The sector 03-C has AF of 40, configuring the most symmetrical section of the entire Chopim catchment. The rosettes of lineament distribution are quite distinct in sectors 03-CR and 03-CL, with predominant E-W direction in the first and N-S direction in the second, but in both sectors, there is a secondary ENE-WSW pattern.

The directions of the first-order drainages in both domains present significant discordance with the directions of the structural lineaments (Figure 8). In sector 03-CR the first order drainages have a greater tendency towards NW, with high density also towards WNW-ESE (preferential direction of the lineaments), NNW-SSE and NE-SW. In the sector 03-CL the preferential direction is WNW-ESE and does not present a clear secondary trend, possessing balanced distribution for almost all the other directions.

Unlike previous sectors, the 03-C has a significant discrepancy between the relief of its two domains. While 03-CL has a more undulating surface (<40%, Figure 10), 03-CR presents many channels with steep slopes, some more elongated and with a preferential NE-SW direction. Also, in comparison with sectors 01-H and 02-TZ it is striking the addition of larger knickpoints on both banks, although no knickpoint of this segment has a value as high as that of 02-TZ mentioned above.

Knickpoint alignments are denser in this sector than in any of the other segments of the Chopim catchment. In the 03-CR there are two striking lineaments, one of E-W direction in the northern portion of the domain and another of NNW-SSE direction, near the eastern boundary, over the Chopim River that extends to segment 02-TZ. The 03-BCE has two other lineaments, the longer one with NNW-SSE direction and another - more dense, where the largest knickpoints of the segment occur (Figure 9), whose direction is N-S. Four E-W direction lineaments occur along the domains, one bordering the southern boundary, two in the 03-CR and one major one over the Chopim River that joins with major lineation of the 02-TZ segment.

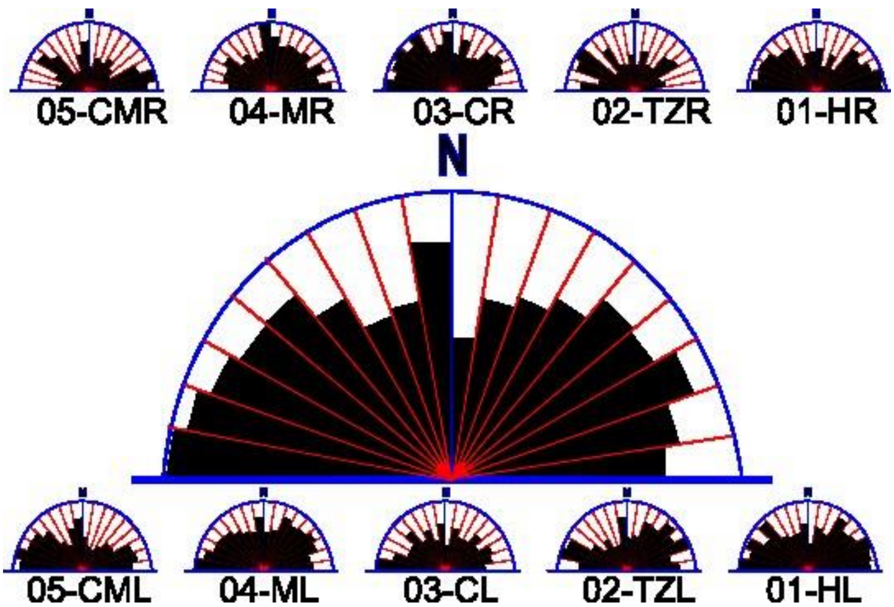

Figure 8. 1 order drainage rosettes. Central rosette uses the data for the entire catchment and the smaller ten for each of the domains.

4.3.4 Marrecas River Sector (04-M)

The segment covering the Marrecas River is the most asymmetric in the Chopim catchment, with AF of 17 (Figure 6). Due to this asymmetry, its two domains have a greater difference in lineament and drainage density than any other pair in the watershed. The structural lineaments of 04-MR (Figure 7) have preferential direction to ENE-WSW and secondary to NE-SW and NW-SE. The lineaments of 04-ML have primary direction to NNE-SSW and NNW-SSE, and secondary to NW-SE, ENE-WSW and NE-SW.

The first-order drainages of the 04-MR (Figure 8) have preferentially NNW-SSE direction and secondarily to ENE-WSW (similar to the structural lineaments) but have relevant distribution in all directions. In the 04-ML the predominant direction is WNW-SSE, but it also has high direction to NE-SW, NNE-SSW, N-S and NW-SE.

The slope map shows some particularities of this segment of the Chopim River watershed. Domain 04-MR is similar to 03-CR, with longer channels of NE-SW direction and steeper slope valleys (40-60%). The central part of the 04-ML also resembles the neighboring domain (03-CL), with softer relief, possessing a few longer NE-SW channels with steeper slopes in their valleys, among which stand out the Marrecas River itself and the other two largest tributaries of the Chopim, the Vitorino and Santana rivers. However, the farthest portion of this domain has higher average slope (Figure 11), exactly in the portion where domain 04-ML is significantly wider than the neighboring domains, 03-CL and 05-CML.

The 04-MR does not have large knickpoints, but has few intermediate ones, while the 04-ML has many of them, although they do not occur in such a high density as in the 03-CL. Near the boundary with sector 03-C, on the Chopim River, is the second largest knickpoint in the entire watershed, a few kilometers upstream from the mouth of the Vitorino River (located in the 04-ML), very close to the circular shaped region of the 04-MR block, on the other bank of the Chopim River.

The main knickpoint orientation of this sector occurs near the variation in slope mentioned in block 04-ML (Figure 9), in the widest portion of the watershed. This knickpoint alignment is curved in shape with a generalized N-S direction but is formed by several segments ranging from NW-SE to NNE-SSW. Two N-S and three NE-SW lineaments occur in the central portion of this domain, the latter overlapping its major rivers. The lineaments in 04-MR are shorter, therefore they do not have a direction as evident as the others. Apparently, this domain has two lineaments with NE-SW direction and a third - more dense - NW-SE direction, which joins the E-W lineament north of 03-CR.

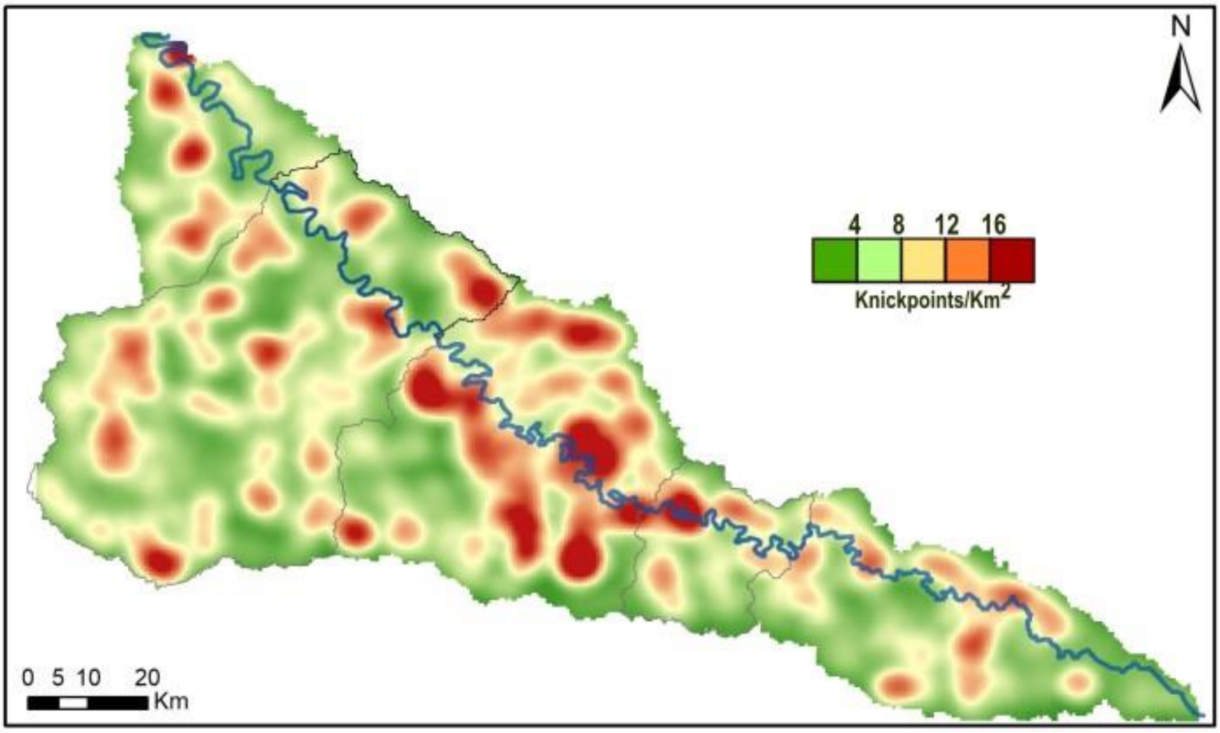

Figure 9. Chopim catchment knickpoints density map (KDM) segmented in sectors.

4.3.5 Chopim's Mouth Sector (05-CM)

The final stretch of Chopim (Figure 6) has an asymmetry similar to that of the initial segment (01-H), with AF of 26. Both domains have a main trend of structural lineaments to ENE and a more tenuous one to NW, but the 05-CML also has pronounced trends to NNW and NNE. The first order drainages of 05-CMR have ENE-WSW direction, as do the structural lineaments, followed by NW-SE and NNW-ESE. In 05-CML there is a clear predominance of WNW-ESE and NW-SE directions, with secondary direction to NNW-SSE (Figure 8).

Sector 05-CM again has similarities between the slope of its domains, as in the two sectors of the upper Chopim. In both domains, the portions with softer relief are isolated, with a predominance of channels with steeper slopes (40-60%, Figure 10). Although in this segment the knickpoints are almost exclusively of the 2nd order and with the occurrence of a few points of intermediate value, the highest knickpoint of the whole watershed occurs very close to the Chopim River mouth in the Iguaçu River, associated with a pronounced elbow anomaly in its course.

The main knickpoint lineament has a NW-SE direction, subparallel to the course of the Chopim River. In domain 05-CML two more tenuous lineations occur with NE-SW direction and in 05-CMR only a single weaker lineation is visible, with E-W direction, which occurs bordering the watershed limits.

5. Morphostructural analysis of the Chopim River

The watershed segmentation method revealed an important variation of asymmetry along the Chopim catchment. Using the Keller and Pinter (1996) criteria - originally applicable to the asymmetry factor (AF) of Hare and Gardner (1985) - it can be seen that the Chopim catchment has a strong asymmetry to the southwest (AF=27), however the analysis of the variation of asymmetry shows that an important (SW) change occurs along sectors.

In sector 01-H the AF is 26, very close to that of the watershed as a whole. However, as Chopim enters sector 02-TZ the watershed asymmetry decreases, reaching the minimum value at 03-C (Figure 6). At 02-TZ the AF is 31, a value that corresponds to moderate asymmetry. When Chopim leaves Palmas/Guarapuava Plateau (Sectors 01 and 02) and enters segment 03-C the AF increases again, reaching 40, a value close to the limit of 40, which corresponds to that of a watershed with slight asymmetry.

When the Chopim River enters the segment 04-M (Figure 6) there is a sharp increase in asymmetry, with an AF value of 17. This increase is even more remarkable due to the absence of anomalies in the course of the Chopim River that justify this variation, just as there are no significant changes on the right bank - in domains 03-CR and 04-MR (Figures 9 and 10) - in any of the four relief factors analyzed. These conditions allow us to stipulate that this variation was not caused by a relative movement between the blocks that compose domains 04-MR and 04-ML, nor by a change in the dynamic equilibrium between them.

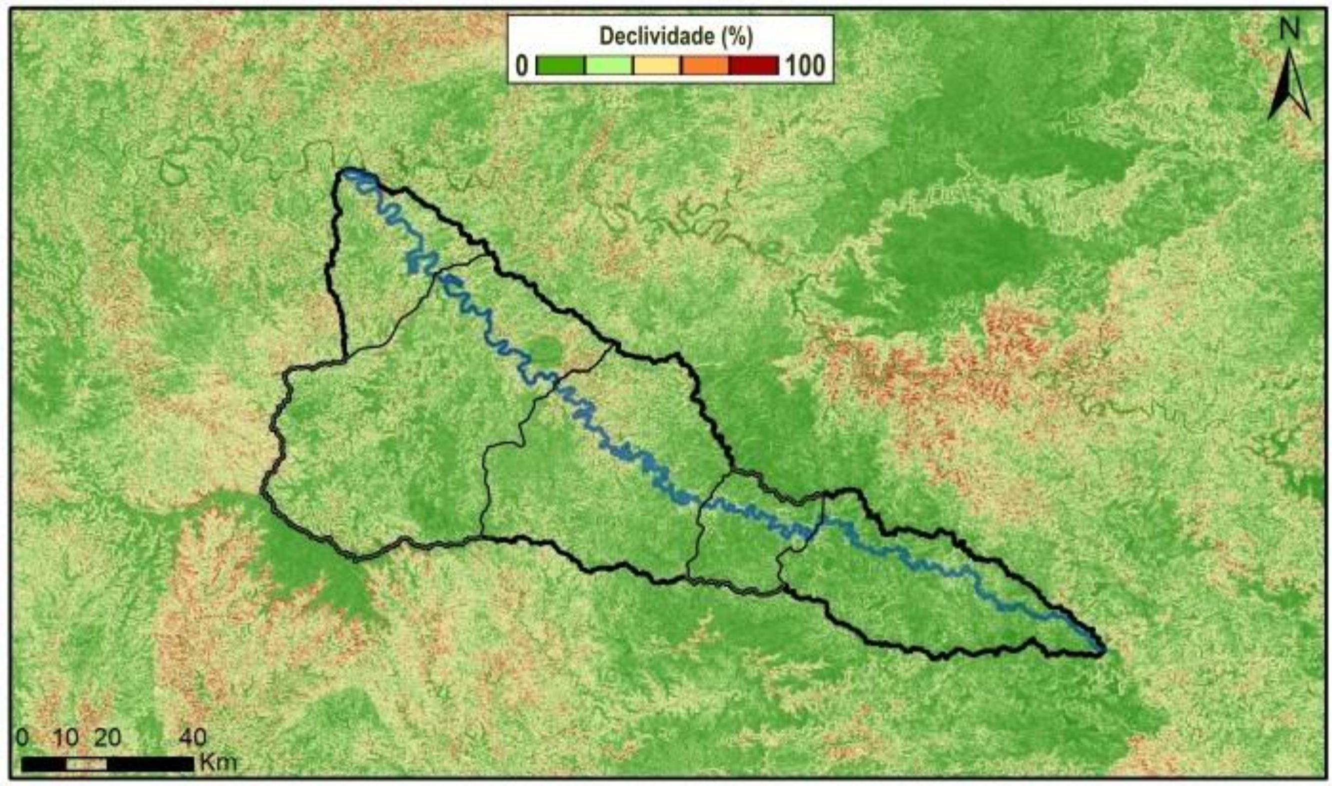

Figure 10. Chopim River surrounding slope map segmented in sectors.

The explanation that seems more adequate for this increment of Chopim catchment's area in the portion that corresponds to domain 04-ML is that the Marrecas, Santana and Vitorino rivers are decapitating the drainages of the catchment of the Cotegipe and Capanema rivers (Alto Capanema Plateau), tributaries of the Iguaçu River that are located west of the Chopim River. This would occur due to the higher hydraulic gradients of these rivers with respect to those of the Cotegipe and Capanema, which are located on the plateau of Alto Capanema, in dissection by the backwearing process of the plateau of Francisco Beltrão (where blocks 03-CL, 04-ML and 05-CML are located). This hypothesis is corroborated by the morphology of the channels of these three rivers, which have valleys with high slope slopes, superimposed on the NE-SW lineaments of knickpoint density. Another factor that points to this explanation are the two textural zones of relief existing in the 04-ML (Figure 11), with the portion located in the center of this domain, near the Chopim River, having a relief very similar to its two neighboring domains on the left margin (03-CL and 05-CML), while the portion near the southwestern limit of the watershed has a more rugged relief, indicating a more intense erosion process in this region.

In the 05-CM sector (Figure 6) the asymmetry decreases again, returning to an AF value of 26, the same as in 01-H. This concordance draws attention due to other coinciding factors between these two segments (01-H and 05-CM) and more tenuously also with 02-TZ. The first point to be highlighted is about the asymmetry factors of these segments, close to the AF=27 value of Chopim (01-H and 05-CM=26 and 02-TZ=31). This similarity is accompanied by another feature that the three segments share, the similarity of relief texture and directional patterns of structures between their two domains. While sectors 03-C and 04-M have marked texture variations between their left and right domains, the other domains show agreement between the pairs (gently undulating relief in the two domains of 01-H and 02-TZ and undulating with a greater number of incised channels in 05-CML and 05-CMR).

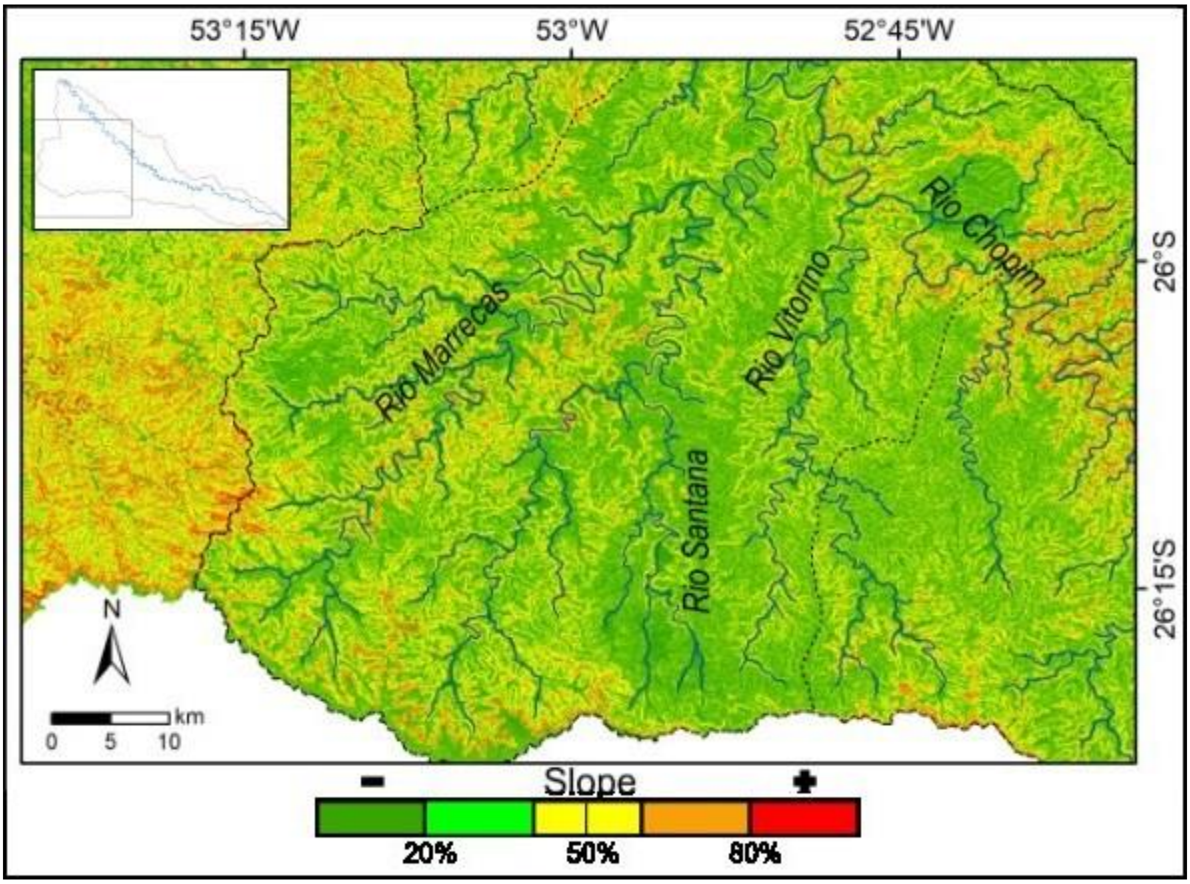

Figure 11. Slope map of the area where the Chopim River tributaries are denuding the Francisco Beltrão Plateau (channels in red and orange to the west).

It is important to emphasize that this abrupt variation in asymmetry and changes in relief texture occurs along with the watershed's widening, concentrated mainly in 04-ML. In the portions where it is narrower, in segments

01-H, 02-TZ and 05-CM, the margins (right and left blocks) have greater similarity and also similar asymmetry factors between them, whereas in the other two sectors the asymmetry has a great discrepancy with the rest of the watershed, at the same time that the blocks start to present greater textural variations between them.

The direction of relief lineations with greater predominance in the Chopim catchment is ENE-WSW (between N60-90E), which occurs in all the domains, both for the structural lineaments and for the first order drainages. The only domain in which this does not appear as a major direction is in the rosette of structural lineations of 03-CL. The WNW-ESE direction appears next in terms of lineation density, but does not occur in domains 04-MR, 05-CML, and 05-CMR. In the other domains it occurs as main or secondary lineations, except in the relief lineations of domains 01-HL and 03-CR, where they occur in an incipient way. These two directions (ENE-WSW and WNW-ESE) are equally the most relevant for the first-order drainages, where at least one of them - if not both - constitute the most frequent ones in the rosette diagrams.

Next, with lesser degree of importance, occur the NE-SW (N30E-N60E) and NW-SE (N30W and N60W) directions, which also appear with great frequency in the diagrams, being NE-SW one of the main ones in the first-order drainage lineations in 01- HL, 02-TZL and 04-ML and in the relief lineations in 02-TZR and 03-CR. The NW-SE direction predominates in blocks 01-HL,02-ZTRD, 03-CRD, 05-CMRD in the first order drainage lineations and in 02-TZR, 04-MR in the relief lineations.

5.1 Fault Zones in the Chopim River watershed

5.1.1 Taxaquara Fault Zone

The expansion of 04-ML is due to the process of decapitation of the neighboring catchments that seems linked to the higher hydraulic gradient of the Marrecas, Santana and Vitorino rivers. The higher degree of incision of these rivers can be observed in the slope (Figure 11) and knickpoint density maps (Figure 9), which suggest that they are embedded in NE faults.

The lineaments that represent these faults extend to the Iguaçu River Fault Zone (IRFZ) through domain 03-CR. The direction of these is coincident with the direction of the TFZ, which was described in the Paraná Sedimentary Basin by Zalán et al. (1986) and later described in more detail in the southern region of the state of Paraná by Peyerl et al. (2018) - in work carried out on the Jordão river, north of the Chopim River and on the opposite bank of the Iguaçu River - who hypothesized that the TFZ extended beyond the Iguaçu River.

Although more evidence this hypothesis still needs to be confirmed, it is possible that the process of erosion of the Alto Capanema Plateau by the expansion of the Francisco Beltrão Plateau is caused by Cenozoic reactivations of the TFZ (Peyerl et al., 2018), which would extend beyond the Iguaçu River and would also section the Chopim catchment and allow the Marrecas, Santana, and Vitorino rivers to fit in (Figure 11).

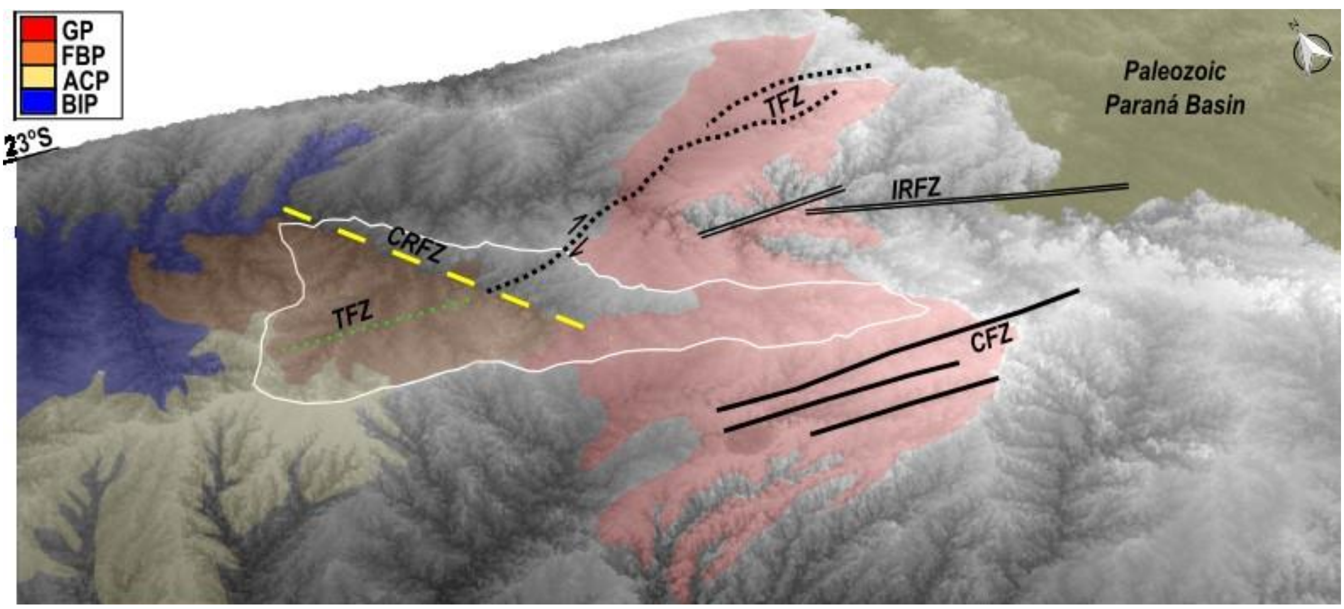

Figure 12. Relation between the major fault zones that cut the Iguaçu River and the Geomorphologic units in the vicinity of the Chopim and Jordão River catchments, modified from Zalán et al. (1990) and Peyerl et al. (2018). Black lines represent the previously mapped fault zones: 1) Dotted - Taxaquara Fault Zone (TFZ), 2) Double lines - Iguaçu River Fault Zone (IRFZ) and 3) Single lines - Caçador Fault Zone (CFZ). The colored lines represent the new fault zones proposed, Chopim River Fault Zone (CRFZ, yellow) and TFZ continuation. Colored zones represents the Geomorphologic plateaus; Red: Guarapuava Plateau (GP), Orange: Francisco Beltrão Plateau (FBP), Yellow: Alto Capanema Plateau (ACP) e Blue: Baixo Iguaçu Plateau (BIP).

5.1.2 Chopim River Fault Zone

The rectilinear form of the Chopim River, with WNW-ESE direction in its upper course and NW-SE direction in its lower course, raises the possibility of its being fitted into a fault zone, herein named the Chopim River Fault Zone (Figure 12). This factor is corroborated by the high incision of the river, with differences in levels between the base and the top of the valley in the order of 100 m, as well as by the presence of the escarpment that configures the limit of its right (eastern) margin. The asymmetry factors used in the Chopim River sectors also corroborate the existence of this fault zone, since even with abrupt variations in the watershed limits, its course is maintained without great changes in direction, nor does it have drainage anomalies that indicate its migration towards the medial sector of the watershed.

The direction of this fault zone is subparallel to that of the Iguaçu River Fault Zone (Zalán et al. 1990), which is located north/northeast of the Chopim catchment. The proximity between the two allows us to infer that they belong to the same system, thus having a synchronous evolution.

The recognition of the Chopim fault helps to better understand how the deformation and the morphological evolution of western Paraná and the Paraná Sedimentary Basin would have occurred. According to Soares et al. (1978) the Paraná Sedimentary Basin, in which the basalts of the Paraná igneous province are inserted, has its deformations caused by the intercalated activation of large NE-SW and NW-SE fault zones present in its basement. In this context, the Chopim River Fault Zone would also reflect the activation of these NW fault zones, as well as the IRFZ, as had already been argued by Zalán et al. (1990).

6. Consideration about the sectorization method

The sectorization of watersheds is a refinement of techniques previously proposed in works involving the analysis of asymmetry factors, such as the application of the factors in affluent drainages (Salamuni et al. 2003) or the use of Cox's (1994) T-factor at the confluence of the main tributaries (Peyerl et al., 2018). Although all these works obtained strong results using the asymmetry factors, the segmentation of the watershed into sectors proved to be a more robust method and easier to apply.

A common problem when use the AF in the subbasins is to display this data on maps, when often the irregular shape of the tributary watershed makes the illustration presents the leopard pattern, as occurred in works made by Salamuni et al. (2003), Buczek and Górnik (2020) and Vidya et al. (2023). Such a pattern helps to identify some minor geological structures and morphostructures, but sometimes it difficult to observe the whole panorama.

As was evidenced by Peyerl et al. (2018) and Salamuni et al. (2020), segment the watershed in zones (upper, middle, lower) results in a better data exhibition, since in this way the AF will aways remains tied to the truck river, don't matter how many subdivisions are made. This concept is the same in the Asymmetry Variation Graph (AVG) and how it was accomplished by Baioni (2007), could be used to link other morphometric data. The sectorization of watersheds advances in this concept because it can be represented on maps, making possible of linking any other structural or geomorphological analysis to the defined sectors, which allows the delimitation of deformed zones and the main structural directions.

Thus, it was possible to recognize the presence of the Taxaquara Fault Zone in the Chopim River, by the relief features and structural trends that are concentrated in blocks 03-CR and 04-ML (Figure 12). Without the sectorization of the watershed, these features would have been camouflaged by their lower frequency in relation to the other directional patterns and the structural analysis would configure them only as a secondary trend.

The analysis of the directional patterns of the first and second order drainages also benefits from this sectorization, because in this way the changes of patterns throughout the catchment can be observed with better refinement, as can be seen in Figures 7 to 10, being able to infer for each block/sector the tensions that would give rise to the lower order drainages. In the same way, the analysis of relief slope and knickpoint distribution is strengthened when used in conjunction with sectors, because thanks to it, areas with different textures (slopes) and knickpoint alignments can be observed in greater detail and linked to the other features analyzed.

Our study demonstrated how the watershed segmentation (sectorization) contributes to better read all other structural and morphometric data, at the same time in which this process integrates all different analyzed parameters. While the main virtues of a method are that it allows for more detailed and reliable observations, the practicality of a method as an innovation cannot be underestimated, especially when applied in large catchments that cover a great variety of geological formations and/or structurally damaged geomorphological provinces, where the application of AF could easily be underutilized. Thus, the sectorization configures a more practical way to observe the asymmetry along the watershed, as well as allowing a better understanding of its structural settings.

7. Conclusion

Watershed segmentation has proven valuable in the analysis of the five factors studied (watershed asymmetry, knickpoint density, slope, structural lineaments, and first-order drainage directions), causing it to be performed separately for each of the established domains. This method allows the data obtained, regardless of its provenance, to be analyzed at levels, starting at the domain and sector scale, at the basin scale, and finally at the regional scale. The integration of the data in sectors, depending on the tool used, allows the distribution of smaller morphostructures to be grouped into zones and the distribution of larger ones (such as the Taxaquara Fault Zone in the case of the Chopim catchment) to have their degrees of influence limited, or even measured, by the defined sectors.

The advance, in terms of morphotectonic analysis, obtained by the factors used in this study allows us to stipulate that this method can be used in conjunction with any morphostructural analysis as well as with structural field data. In the specific case of field data, this routine would allow this information to be interpreted within analogous contexts, grouping the data from all outcrops within the same domain. This would not only allow them to be compared with the structural lineaments but could also assist in obtaining regional morphotectonic characteristics that would in turn provide clues as to the causes of the variations in asymmetry between sectors.

Incorporating the procedure adopted in morphostructural studies allows the data obtained by all the analysis tools used - both by remote sensing and in-field work - to be integrated, analyzed and interpreted over the same parameters, making correlations and patterns easier to identify.

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