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Research Article

A digital elevation model applied to the mobility dynamics in an interfluve of southern Brazil

Um modelo digital de elevação aplicado à dinâmica de mobilidade em um interflúvio do sul do Brasil

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Abstract: In recent years, some topographic metrics (Gilbert metrics) have been proposed to investigate the degree of mobility and stability of drainage divides, through erosion rates between basins that share the same divide. Here, we investigated the mobility dynamics in the main divide of the Ibicuí and Jacuí river basins in southern Brazil, considering several indicators of erosive processes in this region. The mobility and stability of the Ibicuí-Jacuí interfluve were assessed based on the χ and Gilbert (elevation, gradient, and local relief) metrics extracted from the Copernicus DEM (COP-30) and field data, including aerial images. Our results showed that mobility occurs throughout the studied interfluve. In particular, the central region showed a high level of drainage divide mobility, likely due to its geographical location in the Central Depression geomorphological unit, which is dominated by low-resistant sedimentary rocks and relatively low elevations. The results also indicated that the main direction of the interfluve's mobility is from east to west, highlighting that sub-basins from the Jacuí basin are potentially more erosive and, thus, are migrating toward the Ibicuí basin. Once connected, these sub-basins may alter the regional fluvial dynamics of this important region in southern Brazil.

Keywords: Geomorphometry; Erosion; Drainage divide.

Resumo: Nos últimos anos, algumas métricas topográficas (métricas de Gilbert) foram propostas para investigar o grau de mobilidade e estabilidade dos divisores de drenagem, através das taxas de erosão entre bacias que partilham o mesmo divisor.

Sendo assim, investigamos a dinâmica de mobilidade no divisor principal das bacias dos rios Ibicuí e Jacuí, no sul do Brasil, considerando diversos indicadores de processos erosivos nesta região. A mobilidade do interflúvio Ibicuí-Jacuí foi avaliada com base nas métricas χ e Gilbert (elevação, gradiente e relevo relativo) extraídas do Copernicus DEM (COP-30) e dados de campo, incluindo imagens aéreas. Resultados mostraram que a mobilidade ocorre ao longo do interflúvio estudado, em particular, a região central apresentou um elevado nível de mobilidade dos divisores, provavelmente devido à sua localização geográfica na unidade geomorfológica da Depressão Central, que é dominada por rochas sedimentares de baixa resistência e altitudes relativamente baixas. Os resultados também indicaram que a principal direção da mobilidade é de leste para oeste, destacando que as sub-bacias pertencentes ao Jacuí são potencialmente mais erosivas e, portanto, estão migrando em direção à bacia do Ibicuí. Uma vez conectadas, essas sub-bacias poderão alterar a dinâmica fluvial regional desta importante região do Sul do Brasil.

Palavras-chave: Geomorfometria; Erosão; Divisor de drenagem.

1. Introduction

The morphology of Earth's surface is constantly changing due to the dynamic interplay between surface processes (e.g., erosion and deposition) and tectonics (e.g., uplift and subsidence). Additionally, the different lithologies and structures over which relief surface and subsurface process also operate play a relevant role, as different lithotypes resist and respond to erosion in distinct ways (BERNARD et al., 2019; PEIFER et al., 2021). Because of the sensitivity of rivers to relief changes, mainly those located in low-order channels near divides, rivers have been increasingly used as indicators of landscape evolution (ALVES et al., 2022; WHIPPLE et al., 2017; WILLETT et al., 2014). This is especially relevant in fluvial settings where erosion rates vary between adjacent drainage basins, which can drive drainage reorganization process and consequently the migration of divides and changes in catchment areas (WILLETT et al., 2014).

Drainage reorganization refers to the partial or total transfer of flow and the incorporation of drained areas from one catchment to another (WILLETT et al., 2014). Generally, this process occurs between small rivers, mainly between headwaters that share the same interfluve (BISHOP, 1995). Three principal drainage reorganization mechanisms are recognized: fluvial capture, diversion or overflow, and beheading (BISHOP, 1995). Over the last years, studies have shown that drainage divides are more dynamic than expected, and catchments may even undergo drastic changes in contribution areas (CUNHA et al. 2019; SCHERLER; SCHWANGHART, 2020; SALGADO et al., 2021). Because these are very rare phenomenon and are even harder to identify in interior plateaus located in intraplate, tectonic stable settings (DAL PAI et al., 2023) such processes have received little attention, despite the popularity of global digital elevation models (DEMs) and the relatively recent availability of methods for evaluating drainage divide dynamics.

To better understand the dynamics of drainage divides in interior, tectonically stable plateaus, the upper reaches of the Ibicuí and Jacuí river basins, which belong respectively to the Uruguai and Guaíba hydrographic regions of the state of Rio Grande do Sul (RS), configure a potential test-area to apply drainage divide mobility analysis using DEMs. Although the area relief is not marked by contrasting morphologies, several seminal studies mentioned the likely occurrence of capture processes in the drainage networks of this sector (e.g., HAUSMANN, 1962; AB'SABER, 1969). Regionally, Lisbôa and Castro (1998) found evidence for capture process from the headwaters of the Camaquã River System to the Jacuí River System headwaters, as a consequence of headward erosion of the Camaquã basin. Previous analyses based on optical and hypsometric images derived from DEMs of the Jacuí-Ibicuí divide in RS revealed clear exposure to drainage reorganization mechanisms. Thus, in this study, we analyze the dynamics of mobility and stability in the Jacuí-Ibicuí interfluve in RS by determining the degree (intensity) and direction of mobility based on DEM and field data.

2. Study area

The study area is located along the divide between Ibicuí and Jacuí river basins (Figure 1). The Ibicuí river is part of the Uruguay system, that flow westwards to the interior of the South American. The Ibicuí River elevations vary from 43 to 529 m above sea level (asl), with a mean slope of 6.3 %. The Jacuí River flows eastwards into the Guaíba Lake, with elevations ranging from 0 to 1264 m, and a mean slope of 14.6%.

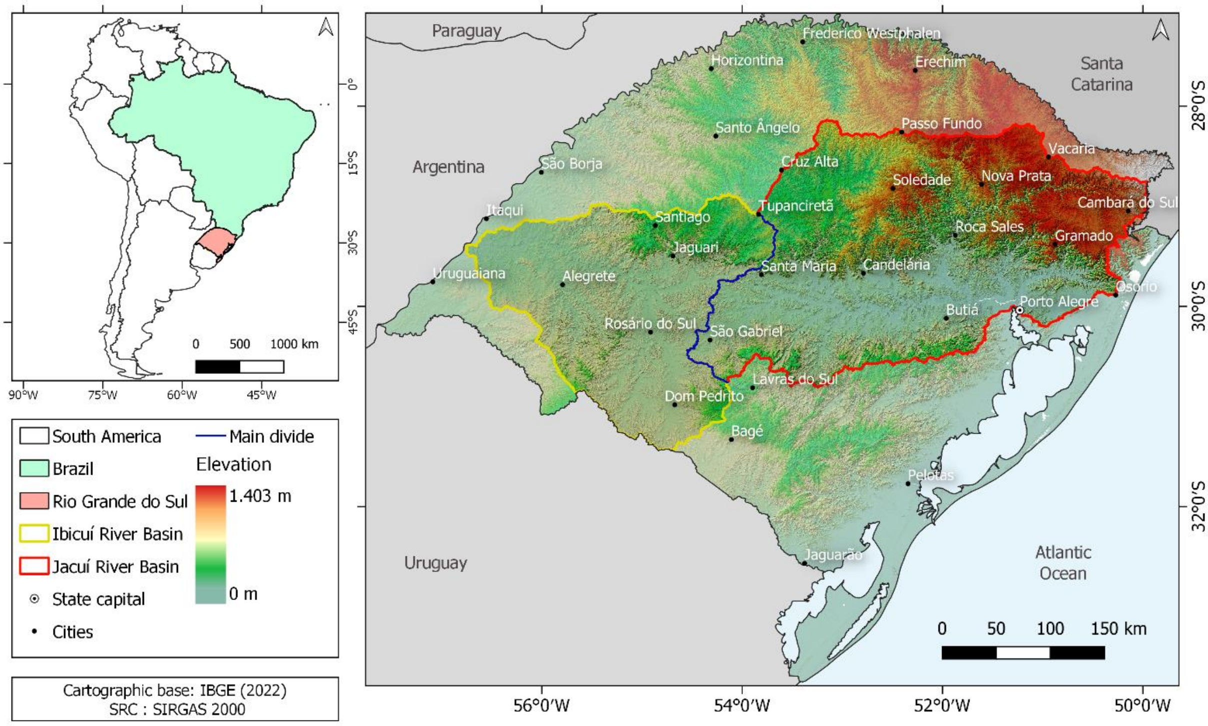

Figure 1. Location of the study area in the central region of the Ibicuí and Jacuí river basins in RS, southern Brazil. Our study focused only on the region of the main drainage divide (blue line).

The study area encompasses three geomorphologic units: (i) the Serra Geral Plateau, (ii) the Central Depression, and (iii) the Rio Grande do Sul Shield (Figure 2a). The Serra Geral Plateau locates the northern part of the study area and is maintained by igneous rocks from the Lower Cretaceous (POLO; JANASI, 2014; BESSER et al., 2018; ROSSETTI et al., 2018) which are part of the Paraná Basin (Gondwana III Supersequence – MILANI et al., 1998) (Figure 2b). Locally, lithotypes are represented by extrusive igneous lithologies from the Caxias and Gramado formations.

In the central part of the study area the Central Depression unit is dominant (Peripheral Depression; Figure 2a), which is composed primarily over sedimentary sandstone and pelitic rocks, with the Pirambóia and Rio do Rastro Formation predominant (Figure 2b). Southwards, sub-basins are located within the Rio Grande do Sul Shield geomorphological unit (Figure 2a), which consists of plutonic and metamorphic rocks, such as the Santa Rita Monzogranite, Jaguari Granite, mafic-ultramafic complex of the Cerro Mantiqueira unit, and Vacacaí metavolcanic units (WILDNER et al., 2006) (Figure 2b).

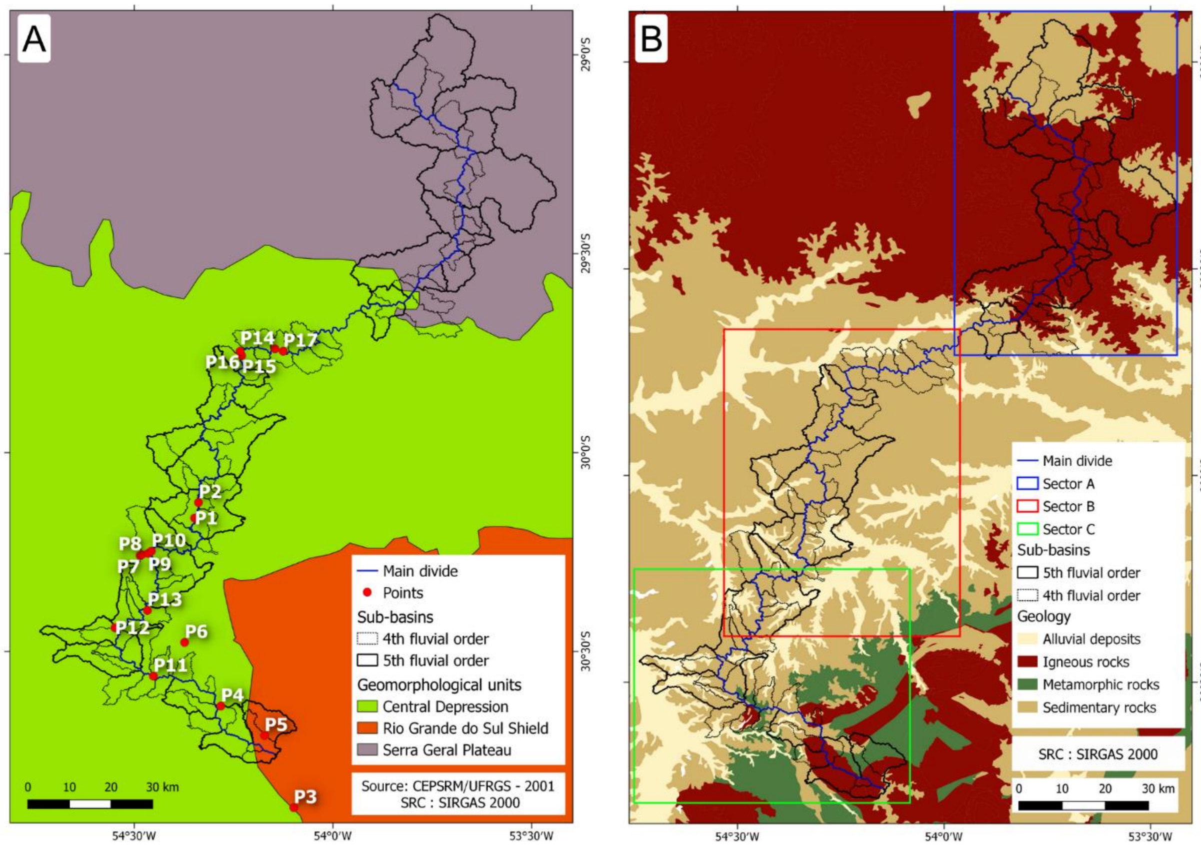

Figure 2. Regional geomorphological units and rock groups in the study area. (A) Geomorphological units covered by the main drainage divide (Ibicuí-Jacuí interfluve), including the location of the fifth and fourth fluvial order analyzed sub-basins. Red dots = spots visited in the field (P1-P17). (B) Main rock groups exposed in the study area, including the location of the main drainage divide and sub-basins.

The study area has a subtropical climate (ROSSATO, 2011), with precipitation ranging from 1200 mm to 2000 mm annually. Higher precipitation rates are recorded in the northern and central parts of the study area, while lower precipitation amounts occur to the south of the Ibicuí and Jacuí river basins. In the case of the Ibicuí river basin, Simioni et al. (2014) found two different climatic dynamics: during medium-low river flow, the recorded annual precipitation is approximately 1200 mm. The other area is characterized by the state's central depression in which the participation normally reaches 1800 mm annually.

3. Materials and Methods

We used a DEM for the topographic analysis of mobility / stability of river basins to investigate fluvial disturbances and drainage network reorganization in the Ibicuí-Jacuí interfluve, southern Brazil.

3.1. DEM processing

The Ibicuí-Jacuí interfluve was assessed using the 30-m spatial resolution Copernicus DEM (COP-30; free access: https://opentopography.org/). This DEM was selected for this study due to its higher altimetric quality compared to other 30-m spatial resolution DEMs as indicated by recent studies (GUTH; GEOFFROY, 2021; PURINTON; BOOKHAGEN, 2021). This DEM was used to extract the drainage network of the study area and corresponding sub-basins. According to previous visual tests, the drainage network was extracted using an area threshold of 1 x 10^6 (1,000,000 m^2) based on functions available in TopoToolbox (SCHWANGHART; SCHERLER, 2014) and Topography Analysis Kit Master – TAK (FORTE; WHIPPLE, 2019), both implemented in Matlab.

The drainage network served the purpose of extracting the fourth and fifth order sub-basins. These sub-basins share a same regional baselevel, that is, the Atlantic Ocean. Fluvial order sub-basins lower than fourth were excluded from this study due to insufficient headwater samples and shorter length of divides for conducting the drainage divide mobility/stability analysis. Following the completion of drainage network and associated sub-basin extraction, a manual and careful selection of the sub-basins of interest was undertaken. In this step, preference was given to sub-basins located closest to the main Jacuí-Ibicuí basin divide. Very small sub-basins or those with few drainage headwaters were excluded from the study. This was done to ensure a statistically more significant sample set for the topographic analysis. For each selected sub-basin, outlet points were identified for semi-automatic basin extraction and subsequent drainage divide mobility analysis, as described below.

3.2. Drainage divide mobility analysis

The outlet points served as the basis for the semi-automatic extraction of sub-basins in Matlab. These points were labeled pairwise (i.e., 1-2, 3-4, 5-6, etc.) so that the algorithm could identify which sub-basins comprised the same divide. The paired drainage divide stability / mobility analysis was done with the help of the DivideTools package (FORTE; WHIPPLE, 2019) using the 'Divide Stability' and 'AcrossDivide' functions. The stability / mobility investigation included a comparative analysis between the χ metric values (WILLETT et al., 2014) and Gilbert metrics (i.e., elevation at the channel head, upstream local relief and upstream gradient; FORTE; WHIPPLE, 2019; WHIPPLE et al., 2018) extracted using a set of headwaters located on both sides of the drainage divide. According to Forte and Whipple (2019), divides are expected to move when erosion rates are contrasting on both sides of the divide, where the greater erosion rate of the aggressor basins drives the migration of drainage divides (WHIPPLE et al., 2017). The erosion rate difference will most likely be driven by differences in the topographic gradient between the two sides of the divide. Therefore, the topographic metrics can be used to assess divide migration as they are topographic proxies for erosion rates. Theoretically, drainage divides tend to move from lower to higher elevations or χ values, while for local relief and gradient, the drainage divide tends to move from higher to lower values (FORTE; WHIPPLE, 2019). Defining whether a divide is stable or not is done by analyzing the degree of overlap or separation between the primary statistics (i.e., mean and standard deviation) of the topographic metrics evaluated for each side of the drainage divide. The drainage divide was assumed to be stable when the mean on one side of the divide overlaps the uncertainty of the mean on the opposite side; otherwise, the divide was assumed as mobile (cf. FORTE; WHIPPLE, 2019). This analysis also allowed classifying the direction/orientation of the divide's movement, in the cases of mobile divides.

The degree of drainage divide mobility was also analyzed in this study, and the mobility of the divides was classified into values ranging from 0 to 4 (Table 1). For a divide with no mobility according to any of the evaluation metrics, the value of 0 is assigned (stable divide, no mobility); a divide with mobility according to just one of the metrics is assigned a score of 1 (low mobility); mobility in two metrics is assigned a score of 2 (moderate); a score of 3 is assigned (high mobility); and a divide with mobility in all four metrics is assigned a score of 4 (very high mobility), indicating that it is most likely to undergo migration and eventual river capture processes.

Table 1. Degree of mobility in 4th and 5th fluvial order sub-basins that share the same drainage divide.

Number of metrics indicating mobility	Valueassigned	Description
No metrics	0	Stable divide, no mobility
One metric	1	Low mobility
Two metrics	2	Moderate mobility
Three metrics	3	High mobility
Four metrics	4	Very high mobility

3.3. Field data

Based on the results of the drainage divide mobility analysis, specific points of interest were visited in the field on May 26th and 30th 2023. In the field, notes on the observed terrain and flights to collect oblique aerial images, seeking to observe and investigate erosive features present in the region were taken. A total of 17 spots (P1-P17; Figure 2A) were visited in the field. Aerial images were captured, except at spots P3 and P6, which were used to describe the relief in the field since there were exposed features of interest for validating the results with the drainage divide migration analysis.

A DJI Phantom 4 PRO remote-piloted drone (RPD), a small, light multirotor device weighing approximately 1.5 kg was used to take the images. It carried a 20-megapixel CMOS sensor with a nominal focal length of 24 mm, which permitted acquiring reference images in the visible spectrum, with wavelengths ranging from 490 to 665 nm (i.e., the blue, green, and red bands), with a maximum image-capture height of 120 m. The spectral bands were also used to produce colored composites (R3G2B1). In addition to the images, it collected terrain points with a model Garmin EtrexHcx GPS. This data was subsequently integrated with the topographic data within a geographic information system (GIS) environment.

4. Results

Through semi-automated procedures done on the DEM, a set of sub-basins located at the Ibicuí-Jacuí divide was obtained and the current stability and mobility dynamic of these sub-basins was analyzed. Below, a general characterization of the studied sub-basins and the results along with their stability/mobility analysis based on the χ metric and the Gilbert metrics are presented.

4.1. Sub-basins and drainage divides

DEM-based drainage investigation resulted in a set of fifth and fourth fluvial order sub-basins located in the main Ibicuí-Jacuí interfluve in RS, southern Brazil (Figure 2A-B). A total of 119 sub-basins were extracted, of which 32 were classified as fifth fluvial order and 87 as fourth fluvial order. Fifth order sub-basins showed an average area of ~ 110 km², encompassing a total of 24 drainage divides. Fourth order sub-basins revealed relatively smaller drainage areas than fifth order sub-basins, averaging around 22 km², with a total of 60 divides. The headwaters of these sub-basins were analyzed using the χ and Gilbert metrics, and their topographic values were compared to each other in order to infer the stability/mobility of the main divide in the study area. For mobile divides, the topographic metrics were also useful for calculating the degree of migration, as well as for establishing the local and regional direction of divide migration. These results are presented in the following.

4.2. Drainage divide mobility and stability analysis

By analyzing the averages and standard deviations of the four studied metrics (i.e., elevation, gradient, local relief, and χ) for each of the 24 drainage divides constituted by the fifth order sub-basins, we found several divides suggested as mobile (Figure 3). From the total of mobile divides, 17 (~ 70%) were indicated by differences in elevation (Figure 3a); 13 (54%) by the gradient (Figure 3b); 15 (62%) by local relief (Figure 3c); and 19 (79%) by the χ values (Figure 3d). Therefore, among the four evaluated topographic metrics, χ was the one that identified the greatest number of mobile divides, and gradient the fewest, for the fifth order sub-basins. Overall, only eight divides were classified as mobile in all four metrics.

The results for the fourth fluvial order sub-basins also showed a significant number of mobile divides (Figures 4 and 5). Out of the total of 60 drainage divides, 47 (~ 78%) were suggested to be mobile according to the elevation metric (Figures 4a and 5a); 42 divides (70%) through the gradient metric (Figures 4b and 5b); 41 (68%) by local relief (Figures 4c and 5c); and 49 (82%) through the χ metric (Figures 4d and 5d). Similar to the fifth order river sub-basins, the χ and elevation metrics resulted in the greatest number of mobile divides, while local relief had the smallest number. Overall, 28 divides were mobile in all four of the studied metrics.

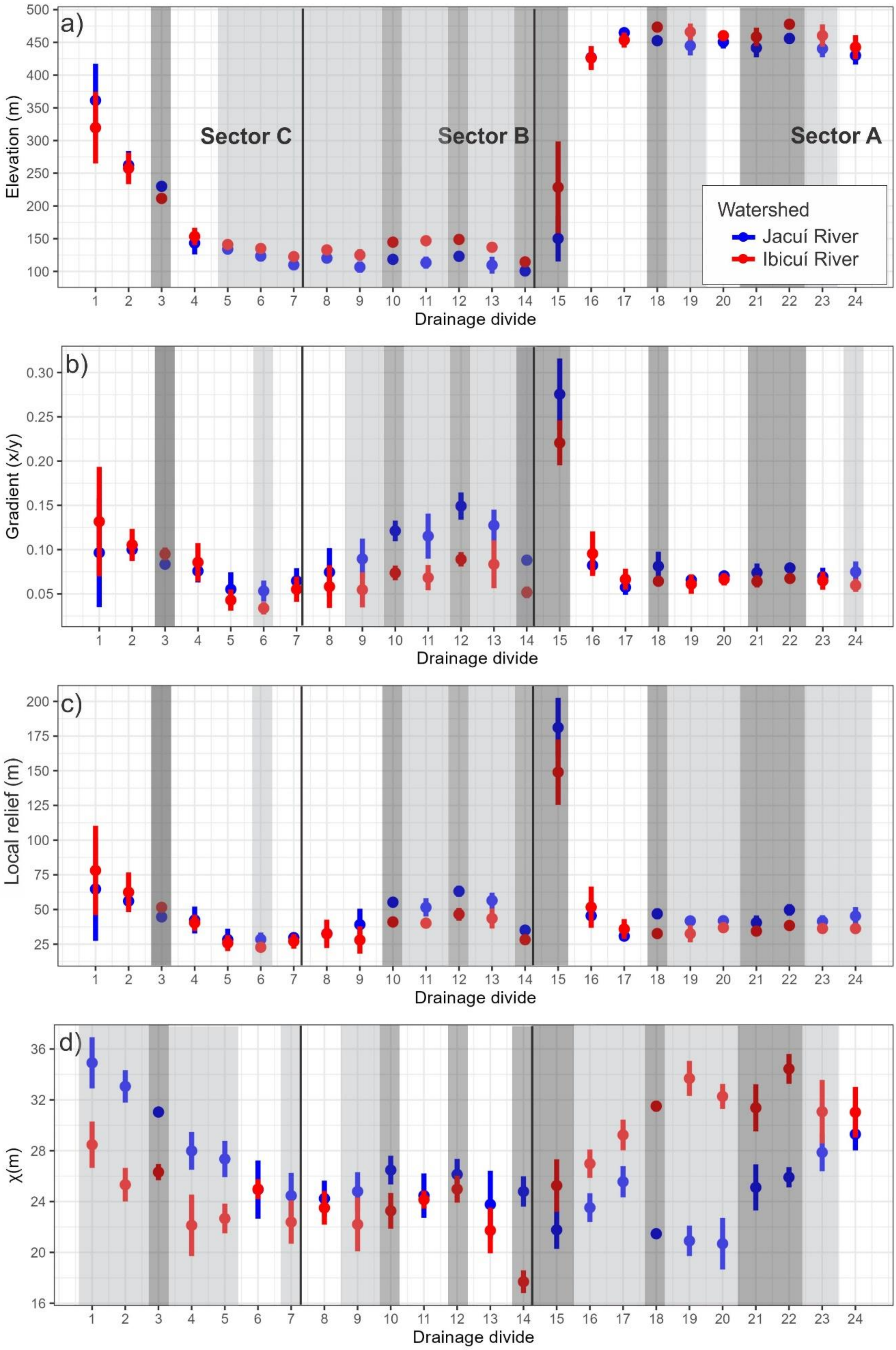

Figure 3. Error bar graph with the mean and standard deviations of the topographic metrics extracted for the fifth order river drainage divides (divides 1-24). (a-d) Elevation (a), gradient (b), local relief (c), and χ (d). Light gray bands indicate mobile divides in each metric. Dark gray indicate divides that are mobile in the four analyzed metrics but pointing to different direction. Sectors A, B and C are shown in Figure 2B.

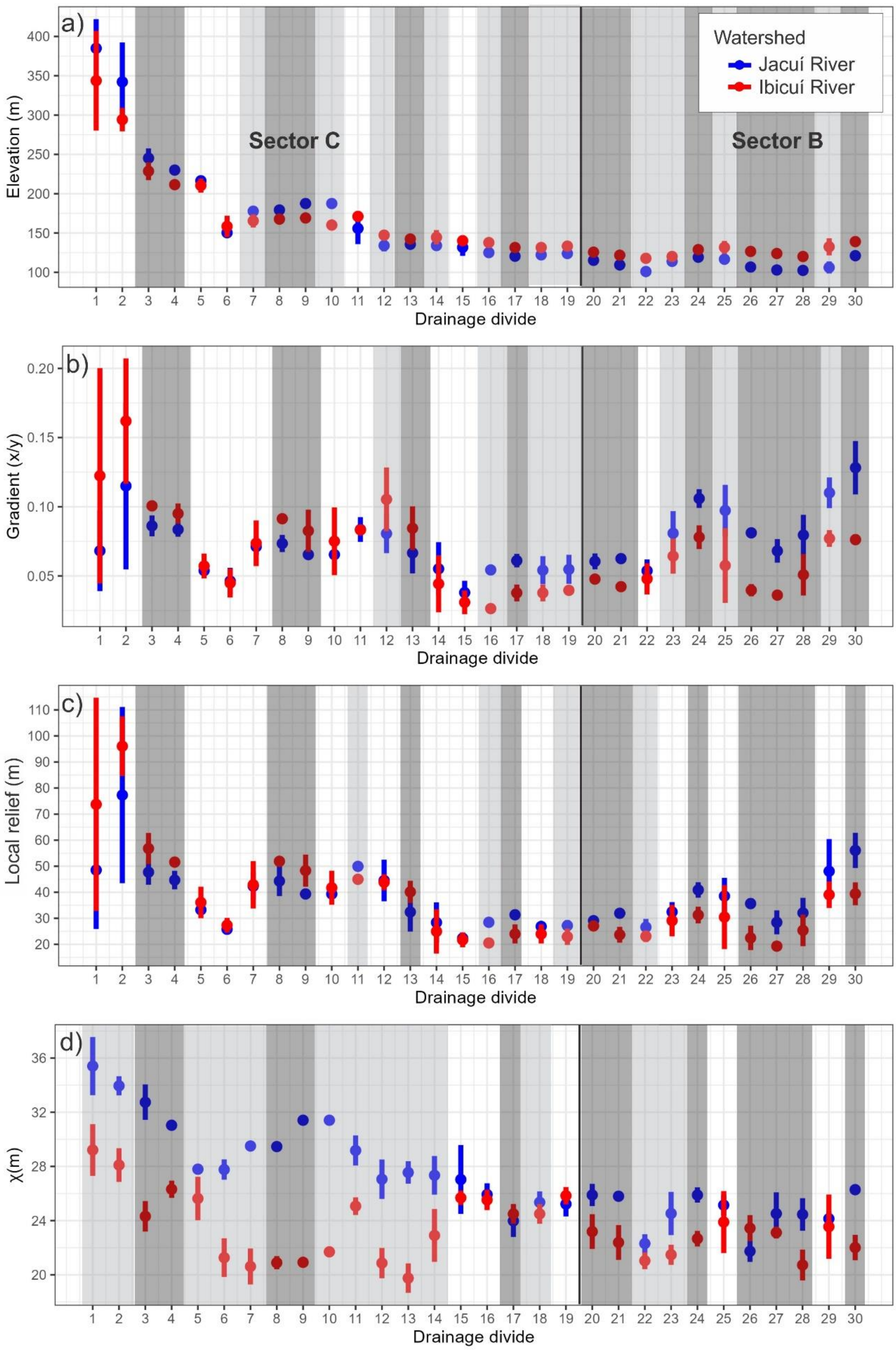

Figure 4. Error bar graph of the averages and standard deviations of the topographic metrics extracted for the fourth order river drainage divides (divides 1-30). (a-d) Elevation (a), gradient (b), local relief (c), and χ (d). Light gray bands indicate mobile divides in each metric. Dark gray indicate divides that are mobile in the four analyzed metrics but pointing to different direction. Sectors B and C are shown in Figure 2B.

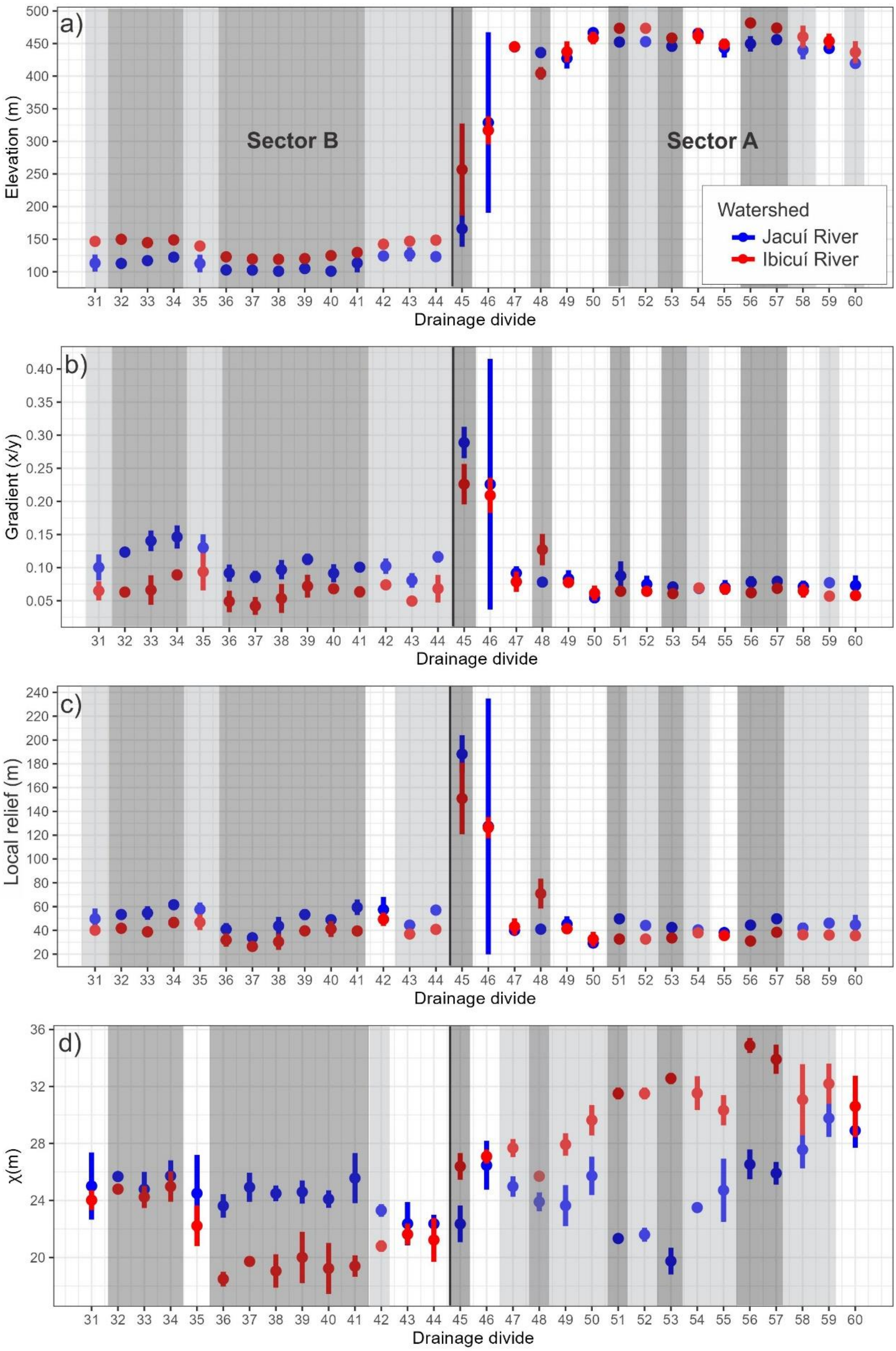

Figure 5. Error bar graph of the averages and standard deviations of the topographic metrics extracted for the fourth order river drainage divides (divides 31-60). (a-d) Elevation (a), gradient (b), local relief (c), and χ (d). Light gray bands indicate mobile divides in each metric. Dark gray indicate divides that are mobile in the four analyzed metrics but pointing to different direction. Sectors A and B are shown in Figure 2B.

4.3. Degree of divide mobility and direction of divide migration

Most of the divides from fifth order sub-basins (58%) revealed high (n = 6) and very high (n = 8) degrees of mobility (Figure 6). None of the divides extracted from the sub-basins of this order were completely stable (i.e., degree 0), indicating that the divides displayed mobility in at least one of the four analyzed topographic metrics. Conversely, the highest percentage of degrees of divide mobility (72%) was found for fourth order sub-basins, with most of them falling into the high (n = 15) and very high (n = 28) classes (Figure 6). It can also be observed that there are two stable divides with no evidence of contrasting values in the topographic metrics.

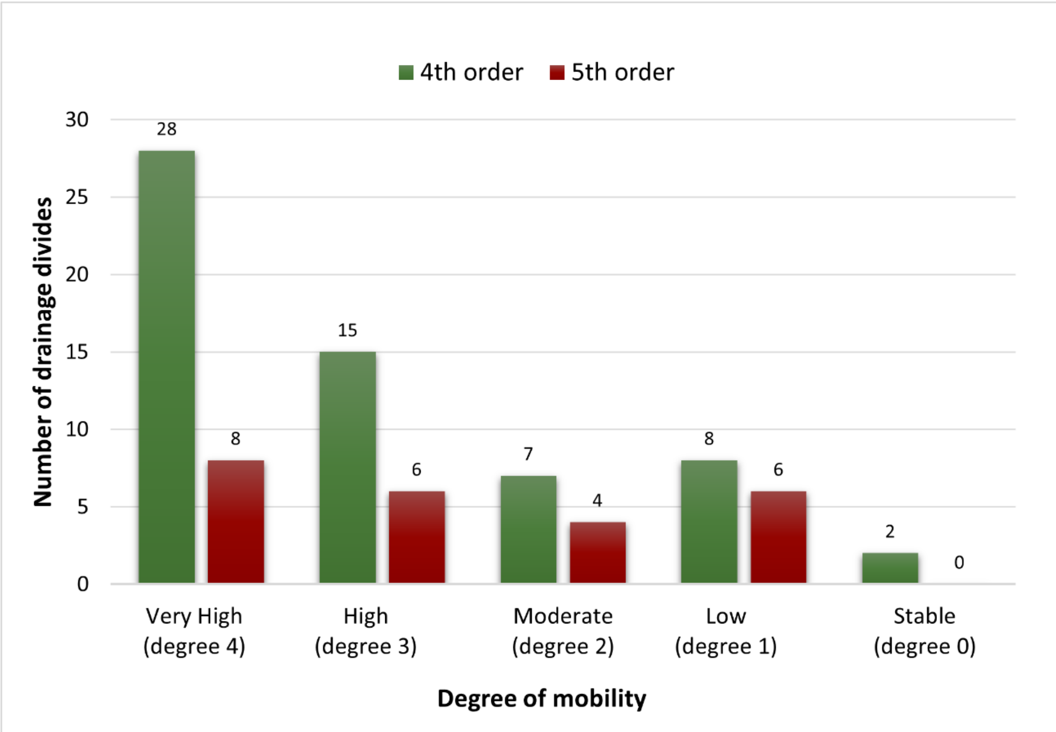

Figure 6. Summary of the degree of divide mobility based on fourth and fifth order sub-basins. See Table 1 for class descriptions.

To better understand the spatial patterns and significance of divide migration in the study area (Ibicuí-Jacuí interfluve), they were further analyzed in terms of geographical distribution (location, degree of mobility, and direction of migration) and the predominance of rock types (Figures 7 and 8) in three sectors (sectors A, B, and C; see location in Figure 2B). Among the three sectors analyzed, sectors A and B presented the greatest occurrence of mobile divides with a high degree of mobility in the case of fifth order sub-basins. Sector C had only two divide segments with a high and very high degree of mobility.

Fifth order sub-basins occurred mainly over igneous and sedimentary rocks (Caxias and Pirambóia formations, respectively), both from the Paraná Sedimentary Basin. These rock types represent ~ 22% and 20% of the drainage area represented only by fifth order sub-basins. In the case of fourth order sub-basins, sector B showed the highest number of mobile divide segments with a higher degree of mobility compared to sectors A and C (Figure 8). Sedimentary rocks from the Pirambóia Formation predominate in these sub-basins, accounting for 20%.

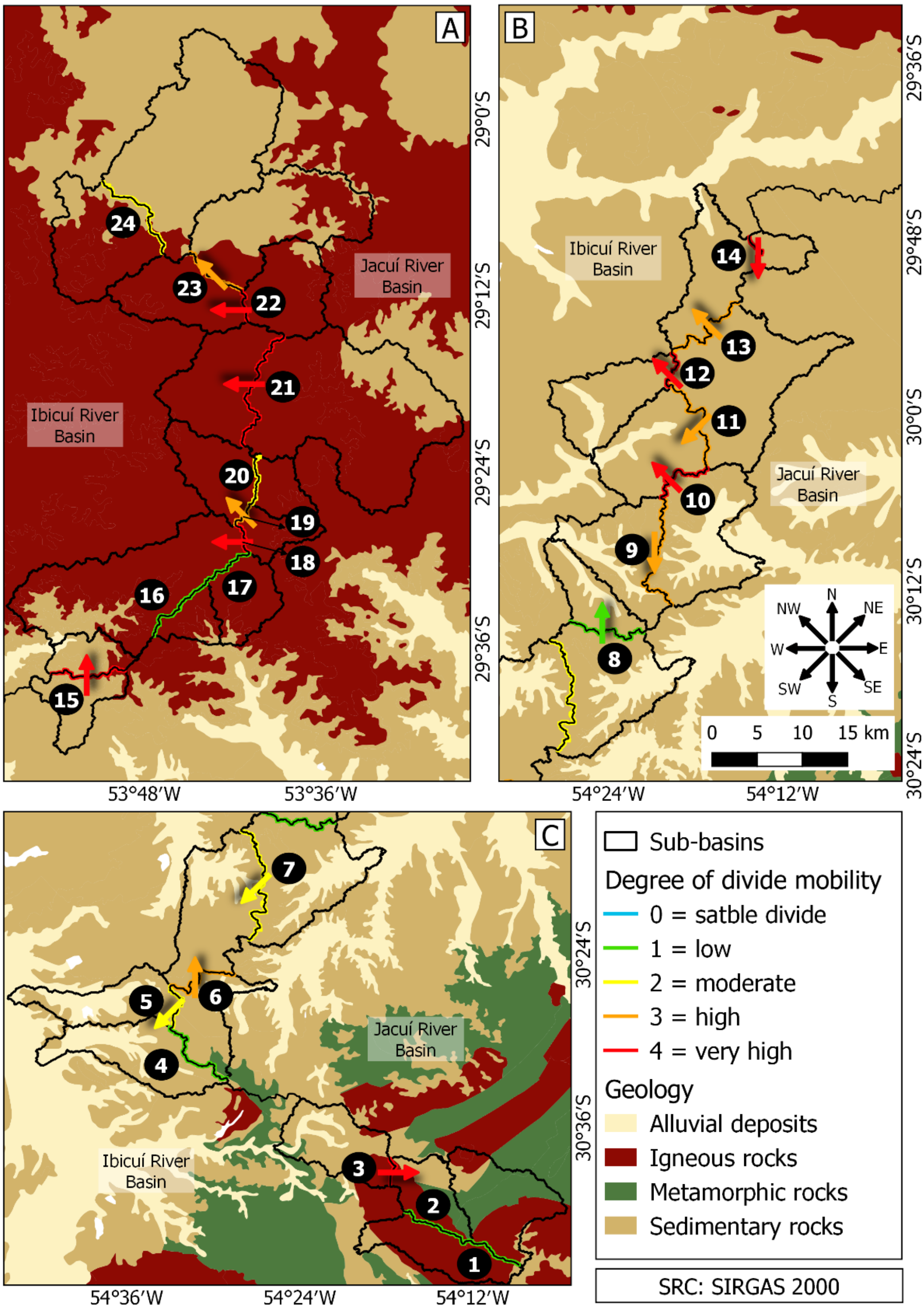

Figure 7. Spatial distribution of the drainage divides from fifth order sub-basins with their respective degrees and directions of mobility, including the distribution of main rock types. A-C) Sectors analyzed in the study area (see Figure 2B for the spatial location of each sector).

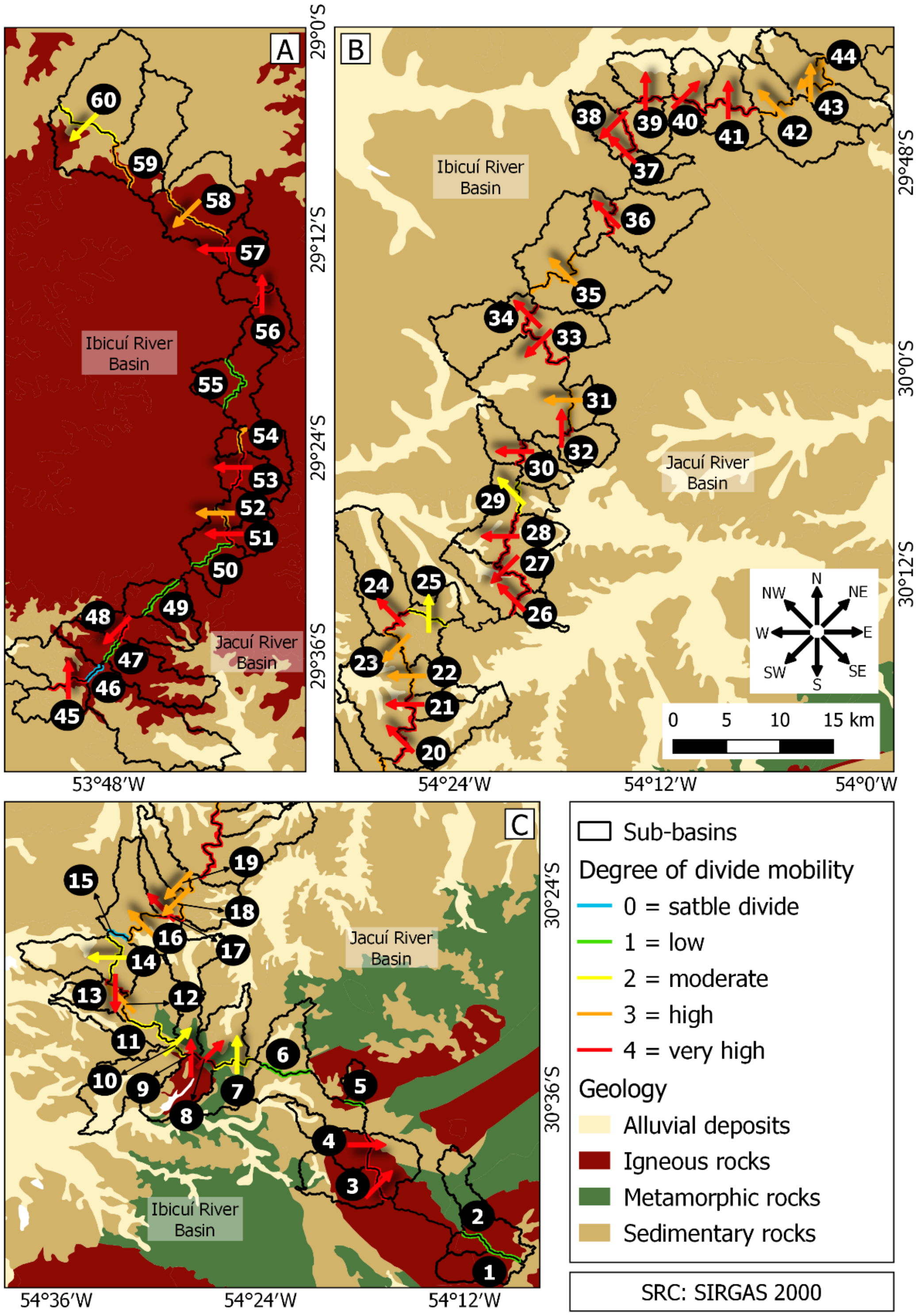

Figure 8. Spatial distribution of the drainage divides from fourth order sub-basins with their respective degrees and directions of mobility, including the locations of the main rock types. A-C) Sectors analyzed in the study area (see Figure 2B for the spatial location of each sector).

The direction of divide mobility was considered only along divides with a mobility degree of four, indicating when all the metrics point to differences on both sides of a given divide (see Figures 7 and 8). The regional mobility direction analysis (Figures 7 and 8) indicates that, in general, divides are moving northwest and southwest, towards the Ibicuí River, with the Jacuí tributaries acting as captors. For fifth order sub-basins (Figure 7), among the three sectors analyzed, sectors A and B are the most unstable. Sector C has only one mobile divide (divide 3), moving eastwards. In this sector, the Ibicuí tributaries are gaining drainage areas from the Jacuí tributaries. This is a local divide segment that do not reflect the general trend of migration in direction of the Ibicuí River basin. Divide

3 is migrating from a sector with high-elevation hard igneous rocks toward less-resistant sedimentary rocks and may be explained by local variations in lithology. In sector B, the Jacuí is the captor system for three divides (divides 10, 12, and 14), which are mobile according to the four metrics. Considering the elevation, gradient, and local relief metrics, the Jacuí tributaries are the captors, whereas χ indicates Ibicuí tributaries as captors. Along sector A, Jacuí tributaries are capturing the Ibicuí tributaries according to all the metrics considered in the four mobile divides (divides 15, 18, 21, and 22 in Figure 7).

For fourth order basins, tendencies are slightly different (Figure 8). Along sector C, six divides are mobile in all the considered metrics, with the Ibicuí system being the captor at divides 3, 4, 8, and 9, whereas only for divide 17 is Jacuí the captor system. For divide 13, Ibicuí is the captor system for gradient, local relief, and χ metrics, while elevation indicates Jacuí as the captor. The sector with the greatest mobility is sector B, with 16 mobile divides, although only along divide 26 do all the metrics indicate Jacuí as the captor system. For the other 15 divides, Jacuí is the captor system (divides 20, 21, 24, 27, 28, 30, 32-34, and 36-41) for elevation, gradient, and local relief metrics, whereas χ indicates Ibicuí as the captor. Finally, along sector A, six divides are mobile in all metrics. Five of them (divides 45, 51, 53, 56, and 57) point out Jacuí tributaries as captors, while along divide 48, the metrics elevation, gradient, and local relief point out Ibicuí as the captor, although χ suggests a capture from Jacuí tributaries.

3.2. Field data description

Based on the aerial images obtained at locations P1, P2, P7, P8, P9, P10, P14, P15, P16, and P17 (see Figure 2A), it was possible to observe features that were not so evident from moderate spatial resolution remote sensing and cartographic data (e.g., regional mapping, optical satellite images, and DEMs). This was particularly noticeable at spot P1, where divide 28 is located (Figure 8B). This divide is moving westward and has a very high mobility (degree 4; Figure 8B). This migration dynamics was evident in the aerial images obtained for this location (Figure 9A-B), where a contrast between the drainage density on either side of the divide was observed. This morphological difference can also be seen in a DEM (Figure 10A), where significant topographical differences are visible on either side of the divide. While one sector in the Ibicuí basin appears to have little vegetation and flatter topography, the Jacuí basin sector presents a larger volume of vegetation in the drainage area and a more rugged topography (Figure 10A). Additionally, some places with erosion scars can be seen, strongly indicating that the divide on the Jacuí side of the basin is advancing toward the Ibicuí side. In terms of dissection of the two basins' topography, the difference continues to be visible along the divide, remaining clear toward the north of spot P2, as shown in Figure 10B.

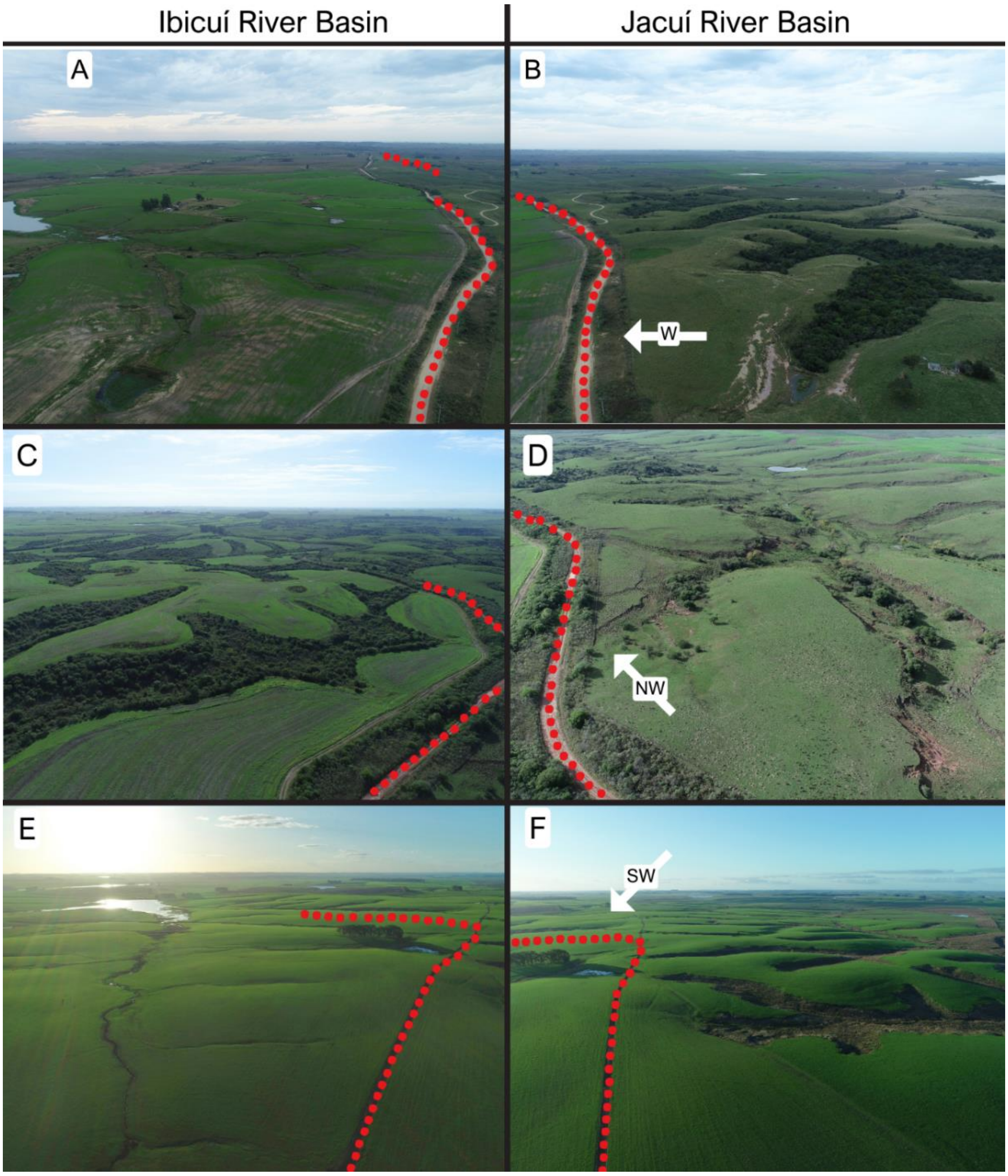

Figure 9. Drone-based aerial images for the spots P1 (A-B), P9 (C-D) and P13 (E-F) in the study area (see location of spots in Figure 2A). Note the contrast between the drainage network on the two sides of the main Ibicuí-Jacuí drainage divide (red dashed lines). White arrows = direction of divide migration.

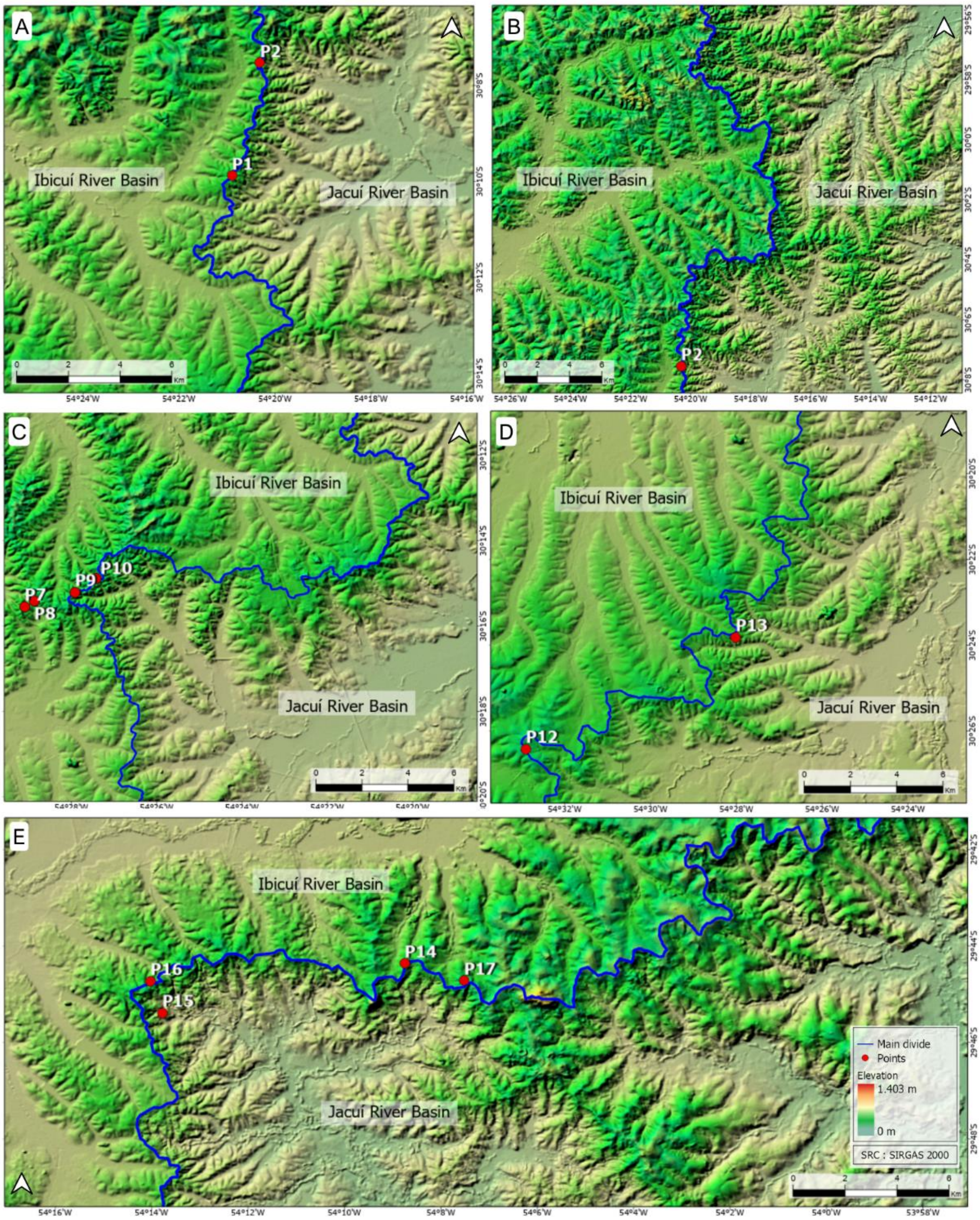

Figure 10. Detailed regional topography of the study area based on the COP-30 DEM, including the location of the main drainage divide. See location of spots (P1, P2, P7, P8, P9, P10, P13, P14, P15, P16, and P17) in Figure 2A. Note the differences in dissection on the two sides of the divide.

Another example is spot P9 located on divide 24 (Figure 8B). This divide is moving to the northwest and also shows a high degree of mobility (degree four, see Figure 8B). Figures 9C-D show two aerial images of this location. It can be seen that the Ibicuí side of the basin has more vegetation (Figure 9C) and a more developed drainage network than the Jacuí side (Figure 9D), which presents less vegetation, though with evidence of erosion along the drainage channels. Along with other divide segments (e.g., 28; Figure 8B), divide 24 also showed westward migration, towards the Ibicuí basin. Visual analysis of the topography of this region in a colored DEM corroborates this topographical difference, in which the Ibicuí basin presents a relatively smoother topography than the Jacuí basin (Figure 10C).

Divide segment 19 (Figure 8C) has high mobility (degree three) and is migrating to the southwest. Upon examining the aerial images of this location (P13 in Figure 9E-F), a smoother topography and drainage network are visible on the Ibicuí side of the basin (Figure 9E) compared to the Jacuí basin (Figure 9F), where the topography is rougher, with deeper valleys, and potentially more erosive, given the evidence of erosion scars along the drainage network. The topographic characteristics of this region (Figure 10D) also show significant morphological differences, with more accentuated and developed morphological features toward the Jacuí side of the basin, strengthening the hypothesis of migration toward the Ibicuí side.

The region around points P14 and P17 (divide segment 38) and points P15 and P16 (divide segment 41; Figure 8B) revealed very high mobility (degree four). Evidence for this mobility includes more accentuated and developed morphological features on the Jacuí basin side (Figure 10E), with significant morphological differences in the topography, corroborating the hypothesis of migration toward the side of the Ibicuí river basin.

4. Discussion

The application of the Gilbert metrics together with the χ metric measured for the Jacuí-Ibicuí divide (Figures 3, 4 and 5) suggests an ongoing divide migration independently of the order of the evaluated sub-basins. The lower elevation divides located in the central portion of the study area (sector B) are the most unstable sector where the eastward-draining Jacuí tributaries seem to be capturing the westward-tributaries from the Ibicuí River. In the divide segments considered, the χ metric presented the most diffuse results, with values constantly pointing to different direction of divide migration as the other metrics (Figures 3, 4 and 5). This is more evident along the Sector B were the χ consistently indicated Ibicuí as the captor system while elevation, gradient and local relief indicated Jacuí as the captor. This reinforces that the χ metric is not so reliable in transient landscapes (FORTE; WHIPPLE, 2019; WHIPPLE et al., 2018), as hypothesized for the study area. A similar tendency was verified by Dal Pai et al. (2023) for the Uruguay-Paraná divide northwards of the study area, where χ and the other Gilbert's metrics did not always indicate the same divide migration direction. This can be linked to the fact that the Gilbert metrics indicate the present-day trend of divide migration whilst χ metric shows the future trend (FAN et al., 2021; SIMOES et al., 2021; WU et al., 2022). Here, the Gilbert metrics showed a more homogeneous pattern and a less noisy distribution of topographical values.

By considering the drainage divides from both the fifth (Figure 7) and fourth order (Figure 8) sub-basins, it can be seen that the central (sector B) and northern (sector A) regions of the study area had greater mobility. These regions revealed the greatest number of sub-basins classified as having high and very high degree of mobility, while the more stable divides, primarily with a low or moderate degree of mobility, lie in the southern portion (sector C) of the study area.

The mobility of the divides may be controlled by various factors (e.g., climate, lithostructure and tectonics; WILLETT et al., 2014; SALGADO et al., 2018; SORDI et al., 2018). In the Ibicuí-Jacuí interfluve the mobility of the divides is most likely related to lithological contrasts, that is, the occurrence of terrain with differing degrees of erodibility (Figures 7 and 8) and the local baselevel which is lower for the Jacuí river tributaries, which drains eastwards into the Guaíba system, than for the Ibicuí tributaries which drain westwards into the continent interior towards Uruguay River. Such proposed lithology control is clearer in sector B where sedimentary rocks from the Pirambóia and Rio do Rastro formations are exposed. These lithotypes are composed by layers of less resistant sandstones and pelitic rocks, which lead to accelerated erosion (ARCANJO, 2011). A combination of lower baselevel and less resistant rocks lead to denudation rates up to ten times faster along the Serra Geral escarpment northwards of the study area (c.f., SORDI et al., 2018). Although the relief is more contrasting on the area studied by Sordi et al. (2018), the lithotypes are the same.

Northwards, along sector A, varying degrees of mobility are found, with very high and high mobility predominating. In this case this mobility can be explained through regional relief, as it is consists a transition zone between the Serra Geral Plateau and Central Depression formed by erosive escarpments. The lithotypes of this sector are dominated by extrusive igneous rocks from Caxias Formation (ARCANJO, 2011).

The southern region is dominated by low-mobility sub-basins, those of degree one, in which one finds various types of granite (i.e., Mozogranito Santa Rita and Granito Jaguari), and thus reliefs with more erosion-resistant rocks, such as the mountainous reliefs mentioned by Arcanjo (2011). In this sector, intrusive igneous rocks are generally more resistant to erosion than the sedimentary rocks of the central portion, according to previous studies in this region (PRÉMAILLON et al., 2018).

In general, regardless of the fluvial order of the analyzed sub-basins, the central region of the study area was the one that held the greatest number of sub-basins of high and very high degree of mobility in contrast to the northern and southern sectors. In looking at the rock types of the study area, it can be seen that the regions with the greatest mobility are those which lie on the sedimentary lithologies of the Paraná Basin. However, to complement the DEM-based results found here, further studies applying, for instance, the rock strength analyses in the region are still needed.

Upon comparing the results of the fourth and fifth order fluvial sub-basins, one can see that the fifth order fluvial sub-basins were more statistically robust, because they encompassed more drainage headwaters than the fourth order ones. For example, divide segment 4 from the fifth order sub-basin analysis used a set of 15 headwaters to perform the topographic metrics, while for the fourth order sub-basins this same total was diluted among three divides. However, according to Forte and Whipple (2019), it is efficient to segment divides to take into account differing behaviors along a divide. In addition, the results were relatively similar for the two fluvial orders analyzed, showing that the central region (sector B) has the highest level of mobility, with the divide generally advancing toward the Ibicuí river basin. The various evidences of divide migration found along the main Ibicuí-Jacuí interfluve based on the remote sensing and field data indicates that this area is undergoing fluvial disturbances, with the dominant trend being a migration toward the Ibicuí river basin, likely related to the contrasting lithological erodibility.

As the fluvial process advances upstream, the sub-basins will be able to connect to each other through river captures (BISHOP, 1995), with transference of flow and drainage area. Once connected, the Jacuí hydrographic basin would increase its drainage area by at least 1,380 km2, if one considers only the migration of the fifth order sub-basins. If connected, the sub-basins of the present-day topography containing the main Ibicuí-Jacuí divide, would experience a change in fluvial landscape, with modification of the local baselevel, river flow direction, and, possibly, changes in biodiversity (e.g. migration of fishes between adjacent basins), as verified in the country's other large river basins (e.g., ALBERT et al., 2018; STOKES et al., 2018).

5. Final remarks

The results obtained from the error bars as well as the aerial images taken in the field show differences such as drainage density, vegetation, and erosion between the Ibicuí and Jacuí Rivers hydrographic basin headwaters. Significant morphological differences in topography were also observed via DEM.

The obtained data also showed that the use of Gilbert and χ metrics together, calculated from the DEM and hydrographic features, enhances the information extracted from the landscape related to drainage divide mobility and stability and that use of only one of these metrics is limiting. Nonethless, our study reinforces that along more symmetrical divides, Gilbert and χ metrics may indicate different divide mobility tendencies since past, present and future dynamics are not unidirectional.

After the analyses undertaken in the Ibicuí and Jacuí River hydrographic basin interfluve, it can be concluded that there is an elevated level of drainage divide mobility, with a dominant past and present tendency of Jacuí River basin advancing toward the Ibicuí River basin. A possible recapture of previously lost areas by the Ibicuí tributaries is envisaged by χ metric.

The results indicate that there is an elevated level of drainage divide mobility, particularly in the study area's central region, which brings together the principle geographic characteristics such as the dominance of the Central Depression geomorphological unit, the predominance of a rocky sedimentary substrate, and relatively low elevations.

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