SL INDEX AS INDICATOR OF ANOMALIES IN THE LONGITUDINAL PROFILE OF PIRAPÓ RIVER

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ABSTRACT – Drainage morphometric parameters are important to characterization of the drainage basin. Main of this study is the application of SL index to analyze the longitudinal profile and to characterize the fluvial valley of Pirapó River basin. These parameters allow the detection of anomalies of drainage that can respond to different factors such as lithology and/or tectonics. The anomalous points detected are located in different areas of drainage basin and show the ungraded river condition. The anomalous points channels are present in the upper and low Pirapó River. SL index for the tributaries also indicate anomalies in their longitudinal profiles. Field data indicate that the areas with anomalous points present asymmetric valleys and terraces, river incision, waterfalls, canyons, among others which normally corresponding to subsidence blocks and faults.
Keywords: Pirapó River, longitudinal profile, SL index, drainage anomalous.

RESUMO – *M. Martinez, E.H. Hayakawa, J.C. Stevaux, J.D. Profeta - Índice RDE como indicador de anomalias no perfil longitudinal do rio Pirapó.* Parâmetros morfométricos de drenagem são importantes para a caracterização da bacia de drenagem. O objetivo principal deste estudo é a aplicação do índice RDE para analisar o perfil longitudinal e caracterizar o vale fluvial do rio Pirapó. Estes parâmetros permitem a detecção de anomalias de drenagem que podem estar controladas por diferentes fatores como litologia e/ou tectônicos. Os pontos anômalos detectados estão localizados em diferentes áreas da bacia e mostram a configuração de desequilíbrio (ungraded) do canal. Os pontos anômalos estão presentes no alto e baixo curso do rio Pirapó. O índice RDE para os tributários também indicam anomalias em seus respectivos perfis longitudinais. Dados de campo revelam que os pontos anômalos localizam-se em vales e terraços assimétricos, locais de incisão do canal, presença de cachoeira, canyons, entre outras feições as quais normalmente correspondem a subsidência de blocos e falhas.
Palavras-chave: rio Pirapó, perfil longitudinal, índice RDE, anomalias de drenagem.

INTRODUCTION

Drainage network has geometric properties that can be quantitatively described (Leopold et al., 1964). Longitudinal profile and the stream gradient index are parameters that allow the morphometric characterization of drainage networks providing subsidies to the knowledge of the geological, structural and some cases hydro-sedimentological factors that control the configuration of drainage basin, as well as its history of evolution (Hack, 1960). The longitudinal profile of a channel determines the gradient of a river and their behavior along the channel from the headwater to mouth (Christofoletti, 1980). The stream gradient index proposed by Hack (1973) allows the identification of anomalies in the longitudinal profile of a river. Combination of these parameters facilitates the identification of variables that control the drainage network as: i) occurrence of more resistant rocks (Lima, 2009), ii) increased input of sediment load and more coarse sediments (Chien, 1984), iii) tectonic activity (Etchebehere, 2000), iv) changes in the base level resulting for sea level variations during glaciations period (Tricart, 1977), v) confluence with tributaries (Knighton, 1998; Etchebehere, 2000) and, vi) by human activities (Fortes, 2003) which can act as possible causes of anomalies in longitudinal profile.

Longitudinal profile and stream gradient index applied to identify the variables that control the network of drainage basin are still scarce in Brazil (Etchebehere, 2000; Martinez, 2005; Guedes, 2008; Fujita, 2009), but are important parameters for morphometric analysis of water courses. In addition rare are the studies in stable tectonic areas. Usually this parameters is applied to river systems related to areas of intense tectonic, as the studies developed by Merrits et al. (1994) at rivers located in the State of California (USA), Brookfield (1998) at rivers located Middle East, Seeber & Gornitz (1983) at rivers located in area with influence of Himalaya Mountains, among others.

In this context, this study proposes the use of longitudinal profile and the index gradient in the drainage basin of the Pirapó River to characterize the valley and identify ungraded stretches in the channel and their possible causes to ungraded configuration.

LONGITUDINAL PROFILE AND STREAM GRADIENT INDEX

The longitudinal profile is a curve obtained from the relationship between height (H) versus distance downstream (L) of a channel (Darton, 1950; Hack, 1957; Christofoletti, 1980). When the obtained profile is concave, commonly is defined as graded profile. Mackin (1948) defined the graded concept as the dynamic equilibrium between erosion and deposition. According Christofoletti (1980) and Etchebehere (2000) in a graded river or some segments of a graded river the rate of degradation and aggradation are similar, then, the river only transport the sediment load. Knighton (1998) stated that the greater extent of channel, greater the concavity of the longitudinal profile.

Several discussions about determination of the difference between a graded and ungraded stream and the graphic representation of a longitudinal profile was conducted by Darton (1950) and Hack (1957, 1959). Based on numerical experiments, Snow & Slingerland (1987) suggested three types of equations: exponential, logarithmic and potential for determining the longitudinal profile according to the controlling variables. Hack (1959) determined that the semilogarithmic graph of a profile allows analyzing a river, where a graded river would appear as a straight inclined line. Thus, any difference between the straight line and the profile could reveal how and where the longitudinal profile of the river would be ungraded. According Hack (1959) conception, the semilogarithimic profile allows the global analysis of the river and indicates the difference from a graded profile highlighting the main points of inflection at the gradient line (knick points) and leading to an interpretation based on geological and geomorphological factors. Hack (1973) considered that the detection of knick points in a longitudinal profile can be quantified from the application of stream gradient index or called SL index (slope *vs.* length).

Hack (1973) proposed the stream gradient index as a practical resource to determine anomalies in the natural concavity at the longitudinal profile. The index allows the normalization of the gradient values and the identification of anomalous points in each section of the river from headwaters to mouth. The stream gradient index by stretch of river is calculated by the equation:

$$SL = \frac{\Delta H}{\Delta L}.L \qquad (1)$$

where ΔH is the difference of altitude between two points in the watercourse, ΔL is the length of this stretch and L is the total length of the channel.

It is also possible to calculate the SL index of a channel in all of its length. In this case the index is called SL_{total} which consider the difference of altitude between the headwaters and mouth and the natural logarithm of the total length of the watercourse, as the equation 2:

$$SL_{total} = \frac{\Delta H}{\ln L} \qquad (2)$$

The model proposed by Hack (1973) allows the identification of anomalous points in longitudinal profile suggesting ungraded channel. The anomalous points in the Hack's proposition are those from the division between the values of $SL_{segment}$ by the values of SL_{total} to obtain values above 2.

STUDY AREA

The study area includes the Pirapó River basin (Figure 1). Located at north of the State of Paraná (Lat. 22º32'30" and 23º36'18"S; long. 51º22'42" and 52º12'30"W), the drainage basin present an area of 5,076 km² and contemplates 29 towns including Maringá, Marialva, Colorado and Apucarana. The basin is located between the Ivaí River basin to the south, Tibagi River basin to the east and some sub-basin of Paranapanema River.

Pirapó River has approximately 250 km of length

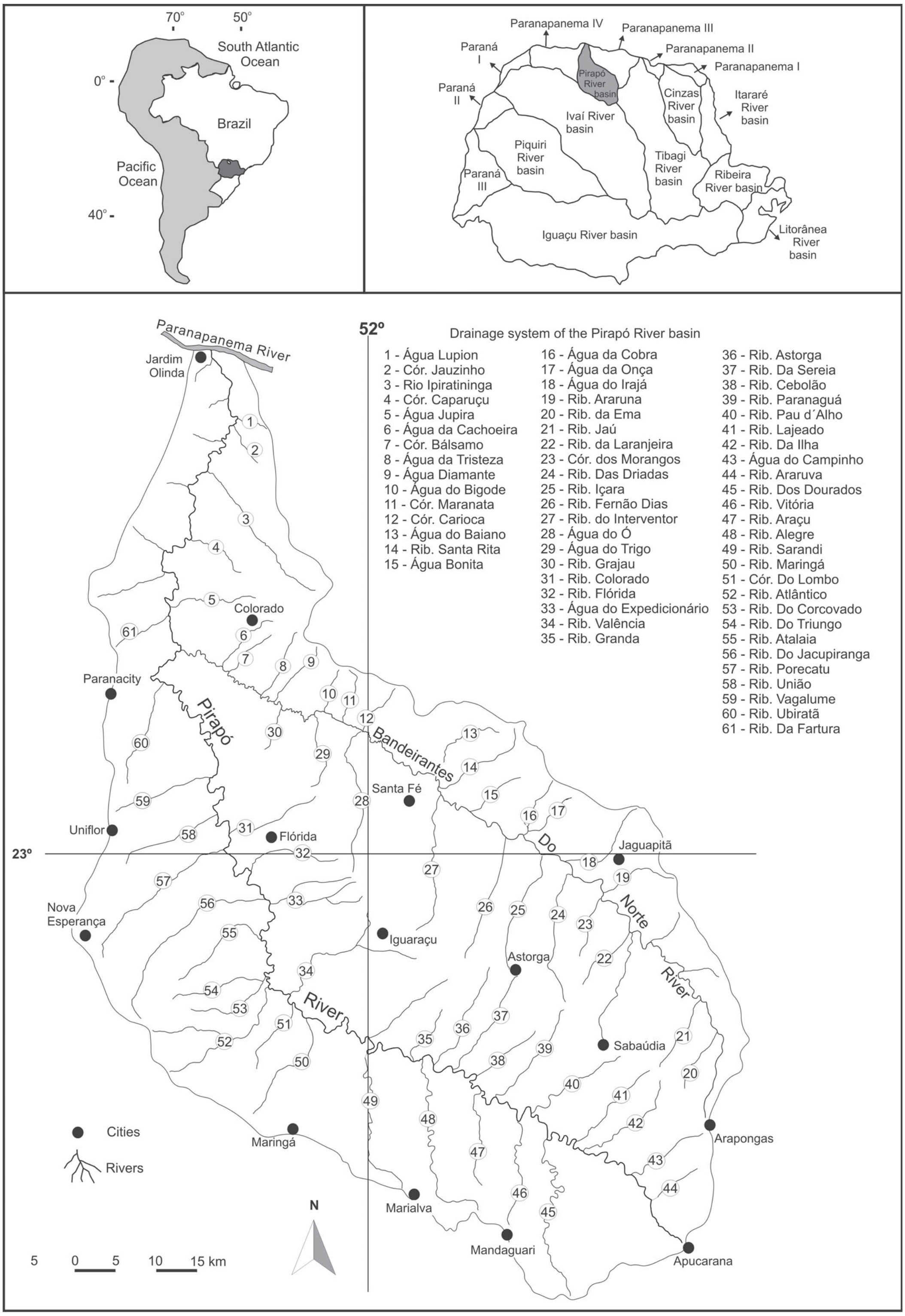

FIGURE 1. Pirapó River basin and their main tributaries.

with headwaters located at Apucarana city (740 m of altitude) and mouth located at confluence with the Paranapanema River (240 m of altitude). Bandeirantes do Norte River is the main tributary (149 km of length), which is located at the right margin of the Pirapó River. Climate in this area is Subtropical Humid Mesothermic (Cfa), with rigorous summers (average temperature over 22ºC), no defined dry season at winter (average temperature of 18ºC) and uncommon frost (Maack, 1968). The vegetation of the Pirapó River basin is Tropical rainforest. Currently is largely replaced by agriculture cultures.

Pirapó River basin is located at Terceiro Planalto Paranaense and contemplates two main lithologies: i) lava flood basalt of the Serra Geral Formation and, ii) sandstone of the Caiuá and Santo Anastácio Formations (Maack, 1968). Outcrops of basalt with 10 to 20 km wide are present continuously in the Pirapó River valley from the headwaters to mouth. In the lower half of the basin basalt is covered by sandstone at the watersheds and the headwaters of some tributaries. The unconsolidated materials is restricted to small patches of Quaternary alluvial deposits associated with the Pirapó River and a sandy and sand-clay material of contradictory genesis. Some authors classify as colluvium-alluvial deposit, know as Paranavaí Formation (Popp e Bigarella, 1975), while others define as pedological origin from the underlying sandstone (Gasparetto, 1999).

Serra Geral Formation presents small fractures and joints caused mainly by the cooling of lava and also by load relief by overlying rock remotion. In some cases, the fractures have tectonic genesis, probably associated with the activity of the Ponta Grossa Arch. Studies developed by PAULIPETRO (1982) in the area noted tectonic lineaments oriented N40-60E and N40-60W.

Drainage basin landscape is formed by gently tilted plateaus, with rectilinear to convex profiles supported by layers of vesicular basalt. In the transition between the upper and middle basin these forms change to isolated hills formed by sandstone of the Caiuá and Santo Anastácio Formations. The middle and lower basin presents a well-dissected relief formed by smooth hills with large convex tops. In this part of the basin the Pirapó River shows a small floodplain. The drainage of the Pirapó River is subsequent/obsequent probably due to epirogenetic movement. Drainage pattern is predominantly subdendritic to dendritic but it is common the occurrence of rectangular to trellis indicating structural control. The drainage in general has relationship with the bedrock, and river runs in the most over rock, with frequent occurrence of small canyons, rapids and waterfalls.

MATERIAL AND METHODS

The data used is this investigation came from geological maps at 1:100.000 performed by PAULIPETRO (1982), the Geologic Map of the State of Paraná at 1:600.000 (MINEROPAR, 1989) and Topographic Charts at 1:50.000 of Teodoro Sampaio, Santo Inácio, Paranacity, Colorado, Centenário do Sul, Nova Esperança, Santa Fé, Astorga, Prado Ferreira, Mandaguaçu, Maringá, Sabáudia, Rolândia, Bom Sucesso, Mandaguari and Apucarana (IBGE, 1975).

In the construction of the longitudinal profile it was measured (by manual curvimeter) the length of the channel between two 20 m contours lines at topographic charts (1:50.000). The values measured were organized in spreadsheets and contained informations such as: higher elevation, lower elevation, difference in elevation, cumulative length, length section, and total length which were used for calculation of the SL index (segment and total). SL index section and total were defined by the equations 1 and 2. Graded and ungraded reaches were identified and measured by the relation between longitudinal profile and SL index and plotted in graphic with the application of the "Best Fit Line function". This allowed the observation of the knick points in the profile and the subsident (below the line) and uplifted (above the line) reaches.

RESULTS AND DISCUSSION

Longitudinal Profile of the Pirapó River

Longitudinal profile of the Pirapó River presents successive concave and convex segments and knick points in the slope line (Figure 2A). The first convex point is located between the 580 m and 500 m contour lines, and has a length of 18 km. At the end of this convex segment there is a segment with graded profile configuration over the next 150 km of the river. At 300 m of altitude (170 to 190 km), close to the mouth of the Bandeirantes do Norte and Ipiratininga rivers, there is other convex segment in the longitudinal profile. The convex area observed in longitudinal profile and in

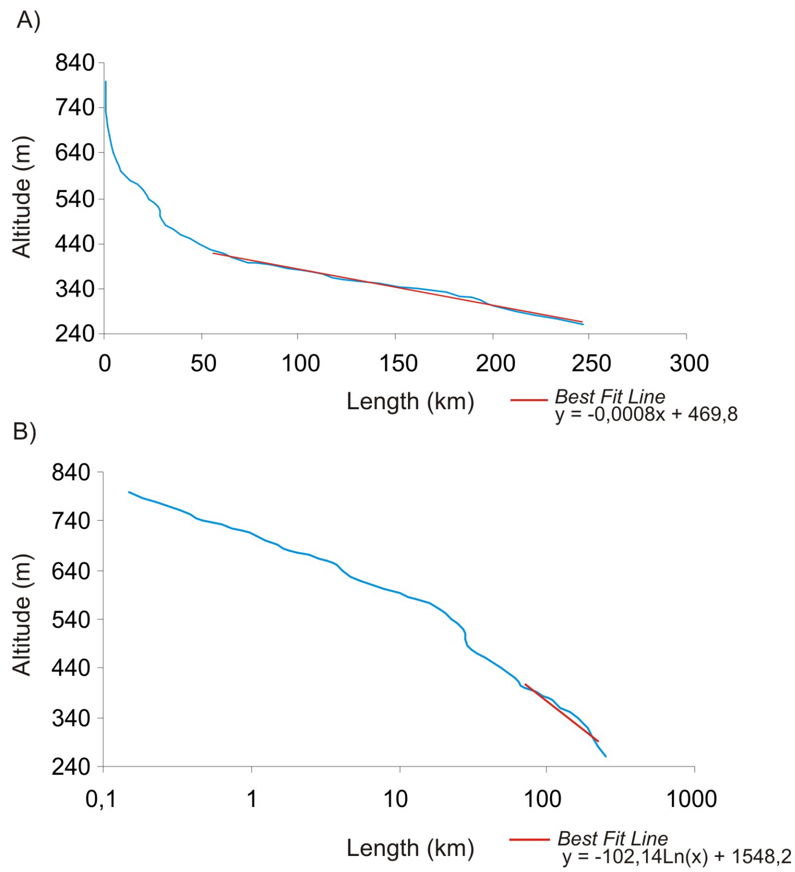

FIGURE 2. Longitudinal profile (A) and Best Fit Line (B) of the Pirapó River.

the Best Fit Line occurs close to the mouth of the Bandeirantes do Norte River and Ipiratininga River (Figure 2B).

Longitudinal Profile of the Bandeirantes do Norte River

Longitudinal profile of the Bandeirantes do Norte River is predominantly concave (Figure 3A). After 60 km from headwaters there is the first anomalous point also observed by the function of Best Fit Line (Figure 3B). In general the Bandeirantes do Norte River presented a graded profile and the anomalous points are restricted to the middle and lower course, close to confluence with the Pirapó River.

Longitudinal Profile of the Pirapó River's Tributaries

Anomalous points are common in many tributaries of the Pirapó River basin. Analysis of tributaries showed: i) occurrence of significant knick points, ii) SL index values higher than those provided by the Pirapó and Bandeirantes do Norte Rivers, iii) sequence of knick point producing steep longitudinal profiles.

Some tributaries of Bandeirantes do Norte River like the Água da Baiana, Água do Brás, Fernão Dias, Ribeirão da Ema and Do Ó creeks and of the Pirapó River like the Uniflor, Caxangá, Flórida, Ipiratininga creeks present knick points at mouth river. Steep slope profiles are observed at the Lajeado, Paranaguá, Aurora, Dourados, Jacupiranga, Araruna and other creeks. Evidence of subsidence and uplifting based on the Best Fit Line are also identified in many tributaries as the Astorga, Coqueiro, Alegre, Triunfo and Ipiratininga rivers.

SL Index For the Pirapó River

Table 1 shows the points with anomalous gradients distributed throughout the drainage basin of the Pirapó River. There are seven points that exceeded the SL index threshold of 2. These points are concentrated in two distinct segments. Those located between the elevations of 480 m to 420 m corresponde to the most significant anomalies, with values ranging from 2.6 to 6.9. This segment comprises about 7.8 km and is located at a distance of 28 km from the headwaters. The second segment located close to the river mouth (between 300 m to 240 m of altitude) present a SL index ranging between 2.3 to 3.0.

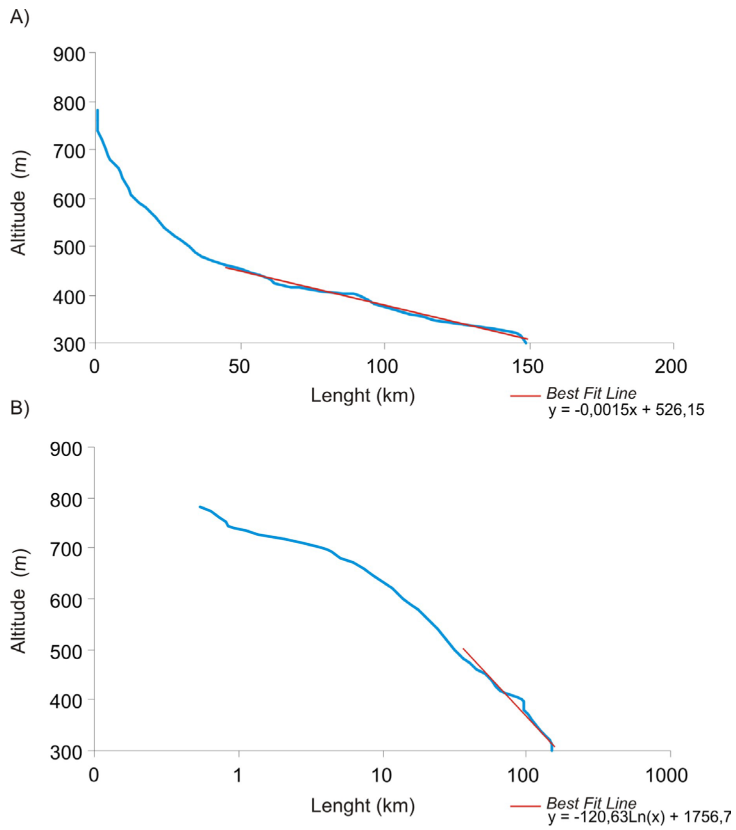

FIGURE 3. Longitudinal profile (A) and Best Fit Line (B) of the Bandeirantes do Norte River.

TABLE 1. Altimetry difference, segment length, total length and SL index to Pirapó River.

Segment	Upper C.L. (m)	Lower C. L. (m)	Difference (m)	Segment lenght (m)	Accumuled length (m)	SL index	Topographic Chart
1	740	720	20	100	100	0,2	Apucarana
2	720	700	20	100	200	0,4	Apucarana
3	700	680	20	250	450	0,4	Apucarana
4	680	660	20	150	600	0,9	Apucarana
5	660	640	20	2000	2600	0,3	Apucarana
6	640	620	20	1000	3600	0,8	Apucarana
7	620	600	20	1400	5000	0,8	Apucarana
8	600	580	20	6100	11100	0,4	Rolândia/Sab.
9	580	560	20	4000	15100	0,8	Sabáudia
10	560	540	20	3800	18900	1,1	Sabáudia
11	540	520	20	2500	21400	1,9	Sabáudia
12	520	500	20	2000	23400	**2,6**	Sabáudia
13	500	480	20	3300	26700	1,8	Sabáudia
14	480	460	20	1500	28200	**4,2**	Sabáudia
15	460	440	20	1500	29700	**4,4**	Sabáudia
16	440	420	20	1000	31200	**6,9**	Sabáudia
17	420	400	20	6250	32700	1,2	Sabáudia
18	400	390	10	7300	40000	0,6	Sabáudia
19	390	380	10	24700	64700	0,3	Sab./Maringá
20	380	360	20	31500	96200	0,7	Maringá
21	360	340	20	20000	127700	1,4	Maringá/Santa Fé
22	340	320	20	40250	167950	0,9	Sta Fé/Nova Esp.
23	320	300	20	26900	194850	1,6	Nova Esp/Pr.City
24	300	280	20	15500	210350	**3,0**	Paranacity
25	280	260	20	17250	227600	**2,9**	Pr.City/T. Samp
26	260	240	20	24250	251850	**2,3**	Teodoro Sampaio

C.L. = map contour line.

The points which the SL index exceeds the threshold coincide with the anomalies observed in the mouth and headwater segments of the longitudinal profile (Figure 4). Anomalies detected in the upper river coincide with the convexity of the longitudinal profile. Anomalies detected in the lower river comprise two sections. The first is located after the confluence of Bandeirantes do Norte River and the second after the confluence of Ipiratininga River. These anomalies also coincide with the convexity represented by longitudinal profile.

SL Index of the Bandeirantes do Norte River

Bandeirantes do Norte River also presents convex segments in longitudinal profile. Two areas exceed the threshold 2 of SL index (Figure 5). First point is located between middle and lower course river between (altitude of 380 m and 360 m). The anomalous point of 4.4 SL index is located close to the Salto Bandeirantes waterfalls. The second anomalous value (3.8) is located between the altitudes from 300 m to 290 m, close to the confluence with the Pirapó River. This convex segment has approximate 100 km of length, and runs over homogeneous lithology and presents low variability of bed load. According to Paulipetro (1982), in these segment the river is strongly controlled by structural factors.

Distribution of Anomalous Points on the Drainage Basin

All anomalies are located on the basalt bedrock and distributed along the river from source to mouth, but are mainly concentrated at upper and lower sectors (Figure 6). At upper basin, relief has high slopes,

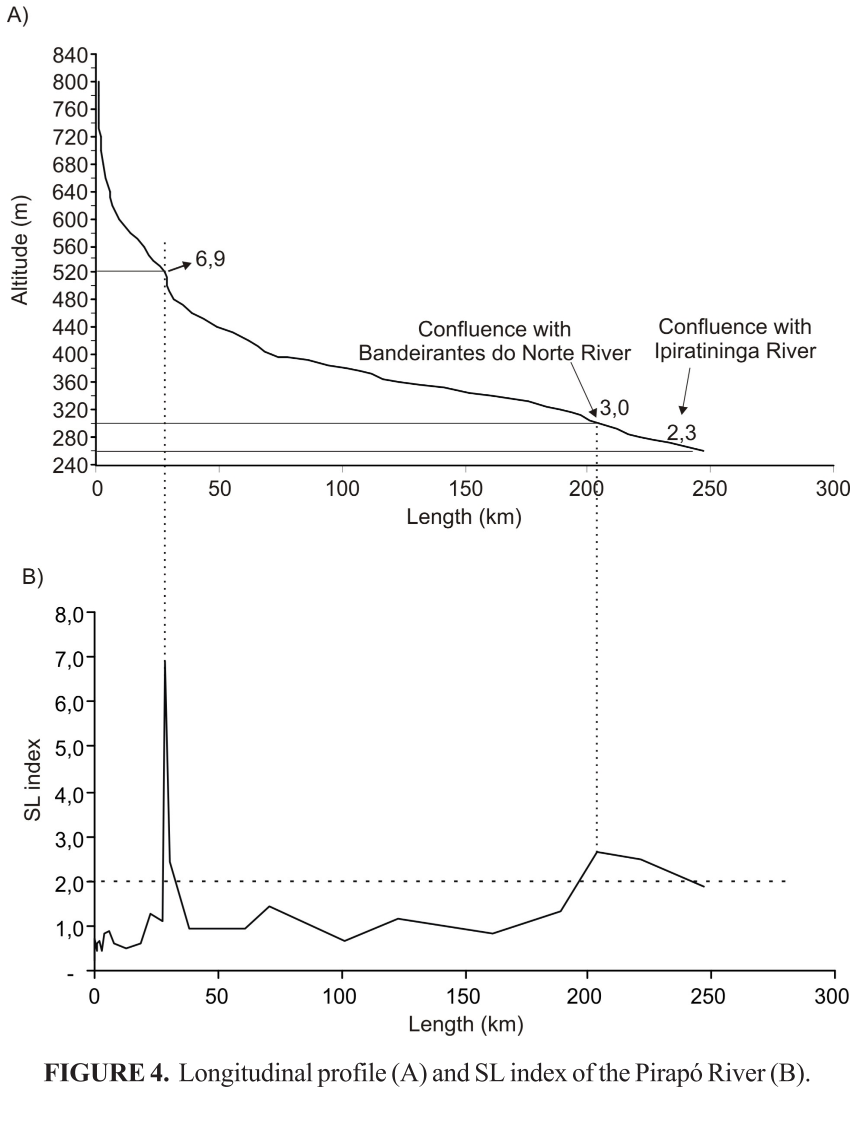

FIGURE 4. Longitudinal profile (A) and SL index of the Pirapó River (B).

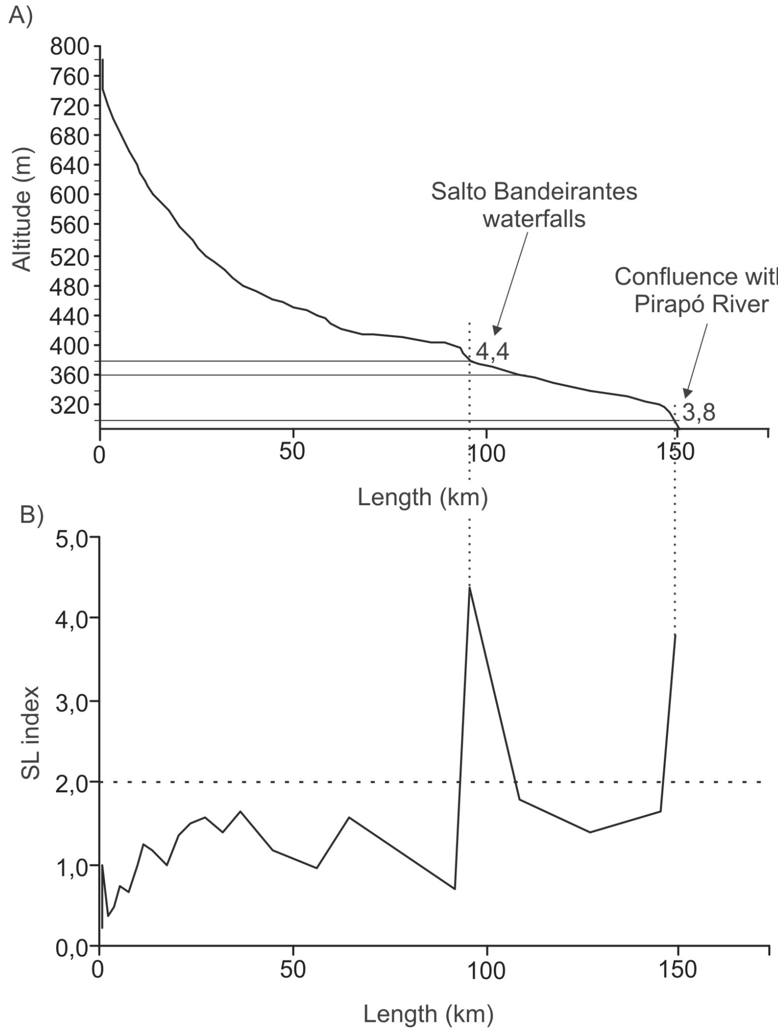

FIGURE 5. Longitudinal profile (A) and SL index of the Bandeirantes do Norte River (B).

conversely the lower basin presents smooth features.

Topographic cross sections at different points in the Pirapó River basin show valleys with distinct configurations (Figure 7). Point A has high slope on the left bank and smooth at right bank. The channel is sinuous and occurs in area subject to discontinuities layers of basalt, developing breaks in right angles in short rectilinear segments. Points B and C in the middle course present smooth valleys with low to very low slopes. Suspended floodplain, terraces and channel incision are common in these points. Point D is located close to the confluence of the Pirapó and Bandeirantes do Norte rivers. This area has high SL index values and asymmetric valley with a landscape formed by extensive hills and smooth divisors. It is common the presence of rapids in the channel and incisions of 10 to 15 m. Point E has high SL index at the Bandeirantes do Norte River. The valley is strongly asymmetric with more convex slope on the left margin and intensive incision. Point F, in the Bandeirantes do Norte River, has SL index value of 4.4 with frequent occurrence of rapids and small falls. Different terrace levels and incision of 3 m to 4 m also are common. Point G in the Dourados Creek presents asymmetric valley and flat bottom. At the right margin observe high slopes and in the left margin note flat areas where note the presence of 3 m high terraces. Sandy clay natural levees are founded in this reach. Inactive gravel deposits occur at different levels. Channel runs over basaltic rocks and presents rapids and small falls.

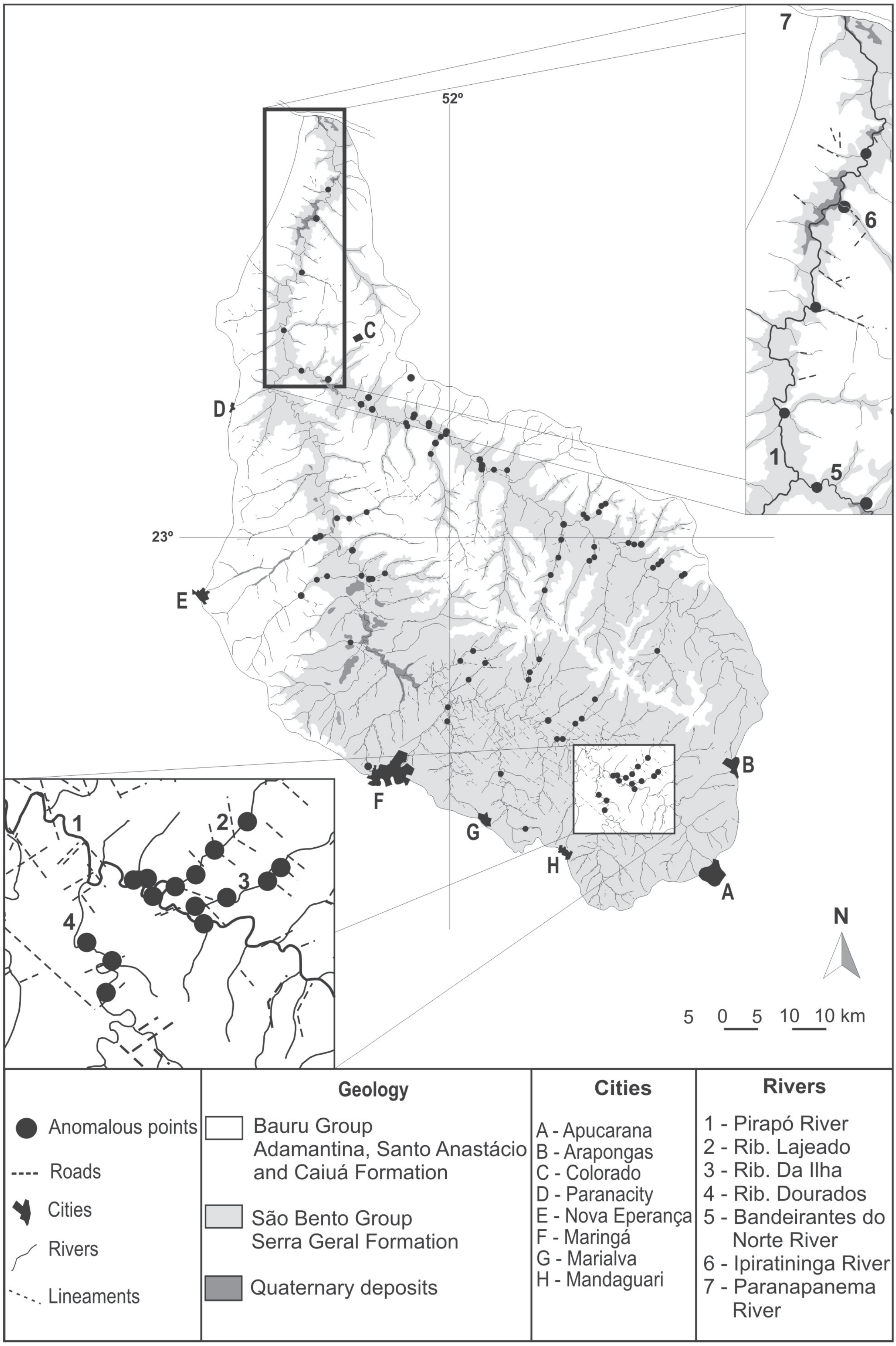

FIGURE 6. Pirapó River basin: Geologic Map and anomalous points distribution.

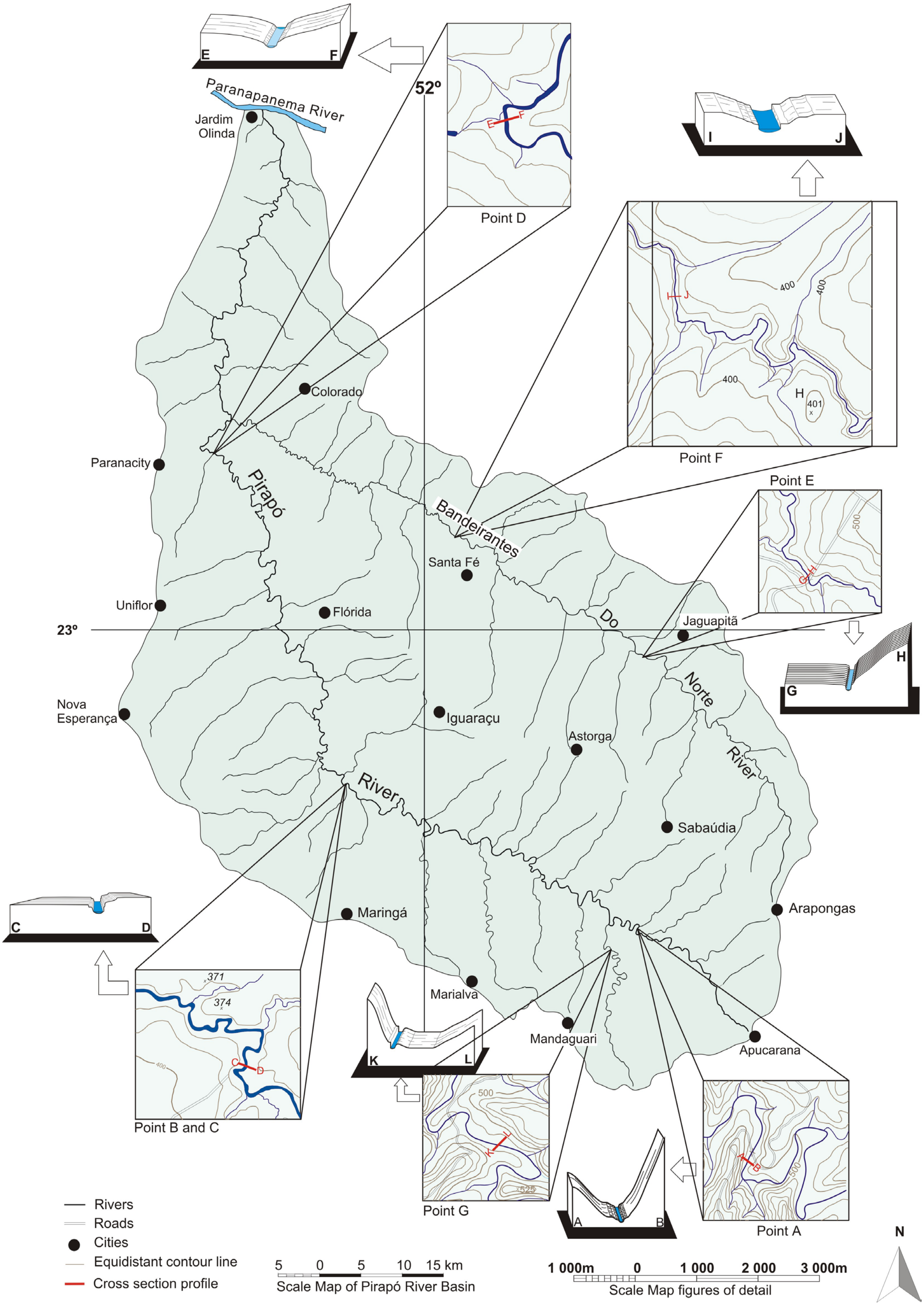

FIGURE 7. Hydrographic basin of the Pirapó River with anomalous points and valley cross sections.

DISCUSSION

The SL index and longitudinal profile allows the identification of anomalous points and the graded intensity of the Pirapó River drainage. Others features as the presence of canyons, waterfalls, rapids, valleys and asymmetric terraces shows the ungraded river condition. Considering that the Pirapó River flow totally on the basalt of the Serra Geral Formation, its possible to minimizes the lithology effects as a possible variable for river gradation. Studies made by Iriondo et al. (2000) in rivers over basalt in the Uruguai River basin generally show a graded profile in most of their courses. The Serra Geral Formation consists predominantly of layers of basalt, apparently homogeneous, with thickness from 20 m to 40 m, bounded at top by layers from 1 m to 2 m of vesicular basalt. In some cases, packages of basalt are not massive and homogeneous, but formed by a series of "traps" ranging from centimeters to meters in thickness. This fact could produce a drainage channel in steps by differential erosion of each layer of basalt and thus generate a large number of anomalous points. However, this factor would cause a randomly distribution of anomalous points and not well defined concentrations in drainage basin river. The localized presence of chalcedony and quarts veins in faults and fractures planes increase erosion resistance but not explain satisfactorily extensive segments with anomalous points.

Neotectonics of the area is not well studied, however, studies developed in others Brazilian rivers, as those present in the Amazonas drainage basin (Sternberg, 1950; Mauro et al., 1978; Bemerguy & Costa, 1991; Costa et al., 1995, 1996, 2001; Hasui, 1996; Souza Filho et al., 1999; Latrubesse & Rancy, 2000; Bezerra, 2003; Ab' Saber, 2004; Silva, 2005; Almeida & Miranda, 2007; Soares, 2007; Rossetti et al., 2008, Hayakawa et al., 2010) report the occurrence of neotectonic events or even the reactivation of ancient structures that can control the drainage network.

In the Paraná River basin, Fortes et al. (2005, 2007) showed the occurrence of tectonic pulse in the Holocene which was responsible for faults that uplifted blocks close to the Ivinhema River area (Mato Grosso do Sul - Paraná State border). Studies developed at the Peixe River basin (left tributary of the Paraná River located in the westward of State of São Paulo), Fúlfaro et al. (2005) and Etchebehere et al. (2005) suggest the evidence of recent tectonic in the low Peixe River. The former suggest that the anomaly at the Peixe River's mouth is due to block movements caused by tectonic events of approximately 34,000 yr B.P. This chronology is given to differences of deposits close to mouth of this river, which were attributed to changes in base level due to tectonic events. Although incipient, these studies show that recent tectonic events may have contributed to evolution of the Paraná River basin.

Presence of channels with evident morphotectonic can be showed as an effective "link between the geometric arrangement of substrate elements and the surface with synchronous crustal deformations (recent tectonic)" (Etchebehere et al., 2005). Examples of tectonic control as faults and their influence in the channel pattern of the Pirapó River are frequents. The several faults in the Pirapó River basin directly influences the local flow of the channels and also contribute to the presence of rectilinear segments. In addition inhibits the formation of sedimentary deposits, that when occurs, are commonly asymmetric. Others features as the presence of knick points, channels with anomalous condition as break in right angles and presence of local level bases also support the possible tectonic control.

Evidence of tilting block tectonics controlling drainage can be seen in many places along the river (Figure 8A, B). In this case a series of uplifted and subsidence tilting blocks control channel sinuosity. Although the use of SL index provided a precise identification and quantification of "ungraded" points, the confirmation of genesis – if tectonic, if related to the internal variability of the packages of basalt or related to climatic changes it's necessary with complementary studies. Probably the ungraded behavior of Pirapó River basin is caused by the conjunction of these factors.

CONCLUSIONS

Longitudinal profile and SL index were essentials to identification of anomalous points at the Pirapó River basin. These morphometric variables allowed the characterization of the main channels and valleys of the Pirapó River basin and the identification and characterization of ungraded areas. Moreover the recognition of these areas enables the discussion about the factors that promote the ungraded in the Pirapó River basin, which may be linked to factors already mentioned above in "Discussion".

Some prospects of study can be defined to try to delineate the involvement of these variables in the development of the drainage basin as: a) detail mapping of segments with highest concentration of anomalous

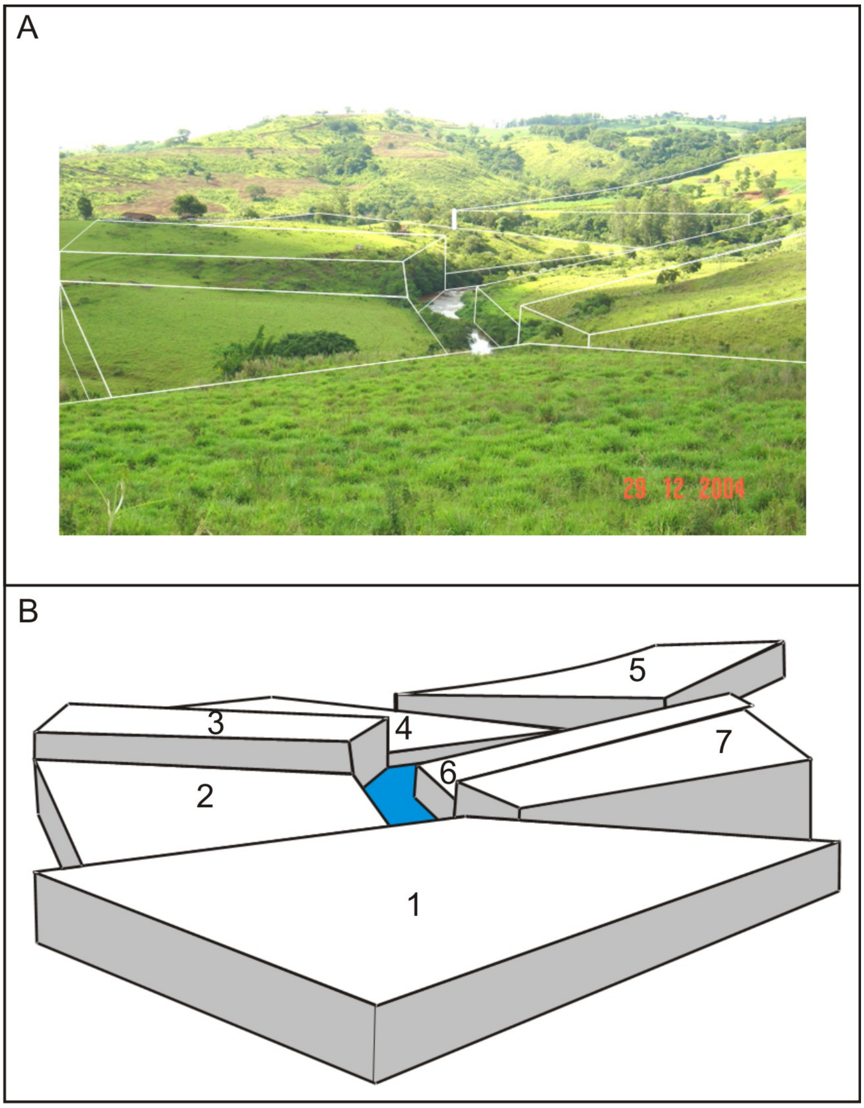

FIGURE 8. A) Configuration of the channel under the morfoestructural control, B) schematic model for the representation of uplifted and subsidence blocks.

points (Hack, 1960); b) elaboration of transversal topographic profiles at this segments (Pazzaglia et al., 1998); c) mapping the alluvial segments and the determination of the size of bed load and their distribution along the river (Knighton, 1998) and, d) identifying the frequently flooded areas (Schumm et al., 2000).

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