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MAURÍCIO ANDRADES PAIXÃO

HYDROGEOMORPHOLOGICAL CHARACTERIZATION OF A CANYON RIVER IN SOUTHERN BRAZIL: A SPECIFIC TYPE OF A MOUNTAIN RIVER

PORTO ALEGRE

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MAURÍCIO ANDRADES PAIXÃO

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Dissertation presented to the Postgraduation Program on Water Resources and Environmental Sanitation of the Federal University of Rio Grande do Sul, as a partial requirement to obtain the doctor's degree.

Advisor: Prof. Dr. Masato Kobiyama

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“Injustice anywhere is a threat to justice everywhere”

– Martin Luther King

RESUMO

Título: CARACTERIZAÇÃO HIDROGEOMORFOLÓGICA DE UM RIO DE CÂNION NO SUL DO BRASIL: UM TIPO ESPECÍFICO DE RIO MONTANHOSO

Rios montanhosos estão presentes em todos os continentes, representando uma boa porção dos territórios. Ao longo das últimas décadas, sua utilização vem aumentando com diversas finalidades, tais como turismo, recreação, manancial de água e ocupação territorial. No entanto, rios montanhosos são menos estudados que rios de planície, embora eventos hidrológicos extremos possam apresentar maior potencial de dano no ambiente montanhoso. Quando considerado rios montanhosos escavados em cânions, esses estudos são ainda mais escassos. Por essa razão, a presente tese buscou identificar parâmetros necessários para caracterizar um rio montanhoso, além de realizar a caracterização hidrogeomorfológica de um rio de cânion localizado no sul do Brasil, o qual faz parte da maior cadeia de cânions da América do Sul e que está inserido na área do Parque Nacional de Aparados da Serra. Para tal, foi realizada uma extensiva revisão bibliográfica, trabalhos de campo, modelagem computacional e análises estatísticas para realizar tal caracterização. Os trabalhos de campo envolveram medições topográficas, batimétricas, vazão, distribuição do tamanho de sedimentos e de unidades geomorfológicas de pequena escala em três trechos do rio do Boi, compreendido. Também foram avaliadas as diferentes condições de resistência ao fluxo nos três trechos. Os resultados indicam que rios de cânion são aqueles sob influência direta do ambiente de cânion em relação aos processos de suprimento de sedimentos, transporte de sedimentos, distribuição do tamanho de sedimentos, padrões geomórficos e hidráulicos. Além disso, cânion, transição e planície apresentam diferentes comportamentos em termos de morfometria dos rios. Desse modo, rios de cânion não são restringidos a rios presentes na paisagem de cânion, mas também aqueles na transição para rios aluviais. A influência do cânion decresce de montante (próximo às paredes do cânion) para jusante (em direção à planície). Além disso, os locais identificados como cânion apresentam maior resistência ao fluxo do que aqueles locais identificados como planície. Como as diferenças são consideráveis, fica evidenciado as diferenças hidrogeomorfológicas em diferentes trechos de um mesmo rio.

Palavras-chave: Caracterização fluvial. Rios montanhosos. Rios de cânion. Geomorfometria. Distribuição granulométrica. Resistência ao fluxo

ABSTRACT

Mountain rivers are presented on all continents, representing an important portion of the territories. During the last decades, their utilization has been increasing by many objectives, such as tourism, recreation, water supply, and land use. However, mountain rivers are less studied than alluvial rivers, even though extreme hydrological events used to reach these areas and cause damages in the mountain environments. Furthermore, when considering rivers carved on canyons, the studies are even more scarce. For this reason, the present dissertation aims to identify relevant parameters for characterizing mountain rivers. In addition, it seeks to perform a hydrogeomorphological characterization of a canyon river located in Southern Brazil, which is part of the most extensive canyon chain in South America, inserted in the Aparados da Serra National Park. It was performed an extensive literature review on mountain rivers. Also, field surveys, computational modeling, and statistical analysis were conducted to realize the characterization. The field surveys include measurements on topography, bathymetry, discharge, grain size distribution, and geomorphic units in three reaches of the Boi River. Furthermore, distinct conditions of flow resistance in the three considered reaches along the Boi River were evaluated. The results indicate that canyon rivers are those rivers under the direct influence of canyon environments concerning sediment supply processes, sediment transport, grain size distribution, geomorphic patterns, and hydraulic conditions. In addition, canyon, transition, and floodplain landscapes present different behaviors in terms of river morphometry. Thus, canyon rivers are not restricted to those rivers presented in the canyon landscape but also those in the transition to alluvial rivers. The canyon influence decreases from upstream (close to the gorge) to downstream (towards the floodplain). Also, the canyon landscapes present higher resistance to flow than floodplain landscapes. As the differences are remarkable, it evidences the hydrogeomorphological differences among reaches in the same river.

Keywords: Fluvial characterization. Mountain rivers. Geomorphometry. Grain size distribution. Flow resistance.

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LIST OF ABBREVIATIONS AND ACRONYMS

ADCP	Acoustic Doppler Current Profiler
CL	Canyon Landscape
DEM	Digital Elevation Model
GIS	Geographical Information System
GPR	Ground Penetration Radar
GUT	Geomorphic Unit Tool
LiDAR	Light Detecting and Ranging
PL	Floodplain Landscape
PNAS	Aparados da Serra National Park
RTK	Real Time Kinematic
TL	Transition Landscape

LIST OF SIMBOLS

Symbol	Unit	Description
a	mm	Largest diameter
A	m^2	Wetted area
b	mm	Intermediate diameter
c	mm	Smallest diameter
CV	%	Coefficient of variation
D	m	Depth
D_C	mm	Roughness parameter ~D_{84}
D_n	mm	Diameter of the *n*-th percentile in the grain size distribution
d_n	mm	Nominal diameter
ff	-	Darcy-Weisbach friction factor
F_R	-	Froude Number
FW	m	Floodplain width
g	m^2/s	Gravitational acceleration
n	$s.m^{-1/3}$	Manning's roughness coefficient
q	m^2/s	Discharge per unit width
Q	m^3/s	Discharge
$q*$	-	Unit non-dimensional discharge
R_H	m	Hydraulic radius
S	$m.m^{-1}$	Channel slope
s		Standard deviation
s^2		Variance
v	m/s	Flow velocity
$v*$	-	Non-dimensional flow velocity
v_{OBS}	m/s	Observed flow velocity
v_{PR}	m/s	Predicted flow velocity
$\bar{x}$		Mean values of measured parameters
W	m	Width
α_{AD}	º	Angle between the beginning of the upstream pool to the end of the downstream pool
α_{BC}	º	Angle between the upstream step to the downstream step
σ_g	m	Standard deviation of the grain size distribution

SUMMARY

Hydrogeomorphological characterization of a canyon river: a specific case of a mountain river

CHAPTER 1

1. Introduction

1.1 General Aspects

Mountain rivers are presented over all the continents. In South America, mountain environments represent up to 22% of their territory. The characterization of a mountain river requires to describe a mountain. There is still no consensus concerning to mountains classification due to their esthetics and/or morphological patterns. As a consequence, mountain rivers classifications are also a challenge for scientific communities.

During the last decades, several ways for classifying rivers have been developed depending on the analysis subject (Horton, 1945; Strahler, 1957; Stevens et al., 1975; Schumm, 1977; Montgomery and Buffington, 1997; Zimmermann and Church, 2002; Buffington et al., 2003; Brierley and Fryirs, 2005; Church, 2006; Thompson et al., 2006; Buffington et al., 2009; Buffington, 2012). Some of them are suitable for describing mountain rivers. However, with the advance in the knowledge of hydrogeomorphological processes, classifying a river becomes even more challenging and complex.

Wohl (2010) commented that the most prominent characteristic is the channel slope when considering mountain rivers. However, it is not enough for classifying a river. Fryirs et al. (2007), for example, commented that the water and sediment move forward quickly in a mountain river, and hydrogeomorphological processes are significant. Additional characteristics, such as variation between the minimum and maximum discharges, the occurrence of debris flow, and entrenchment ratio, were analyzed (Buffington, 2012; Church, 2006). Furthermore, entrenchment ratio (Rosgen, 1994), sediment load (Brardinoni et al., 2015), and large sediment size (Tsakiris et al., 2014) were also reported. Monte et al. (2021) commented that extreme hydrological events are often observed in mountain regions.

Kobiyama et al. (2018) commented that the occupation and use of mountain catchments had been intensified in the last decades. The usefulness of mountain rivers includes different purposes such as tourism, recreation, hydroelectric energy, etc. (Paixão and Kobiyama, 2019).

As mentioned above, mountain environments are subject to the occurrence of extreme hydrological events. Therefore, mountain environments should be further studied to prevent damages related to extreme events. However, rivers located in mountain environments are less studied than lowland rivers (Aberle and Smart, 2003). The studies about mountain rivers carved on canyons are even more scarce.

Canyon rivers can be thought those under the direct influence of canyons on their hydrogeomorphological characteristics. In other words, canyon rivers are not restricted to those inside the gorges, but also at the transitions to alluvial fans whereas influenced by the canyons.

An extensive literature review shows advances in knowledge related to valley formation, fluvial processes, sediment transport, and management of canyons (Table 1-1), where most of the studies were conducted in North America, especially in the Colorado River, after some investments in research in this region. However, there is a lack of knowledge to define the extension of canyon rivers and their transitions to alluvial rivers. Thus, in terms of first surveys of canyon rivers, geomorphological changes, sediment transport processes, and flow resistance are essential tasks to advance the scientific knowledge on these kinds of rivers.

In addition, just a few studies tried to identify the river flow structures in canyon rivers (i.e., Waele et al., 2010; Venditti et al., 2014; Gasparini, 2014). Nonetheless, no studies have been reported concerning the flow resistance and the transition from canyon to alluvial rivers in these environments. Studies involving flow resistance in a high-gradient channel have been done in the last decades, both in flume experiments (i.e., Rickenmann, 1991; Maxwell and Papanicolau, 2001; Aberle and Smart, 2003) and field-based (Lee and Ferguson, 2002; Comiti et al., 2007; Afzalimehr et al., 2011). However, they can not be directly compared to canyon rivers.

Table 1-1 – Studies on canyon rivers

Authors	Region	Location	Main Subject	Sediment Transport	River Classification	Field Survey
Inbar and Schick (1979)	Middle East	Jordan River	Bedload transport	YES	NO	YES
Vannote and Minshall (1982)	North America	Salmon River	Fluvial processes	YES	NO	YES
Webb et al. (1999); Schmidt et al. (1999)	North America	Colorado River	River flow	NO	NO	YES
Venditti et al. (2014); Gasparini (2014)	North America	Fraser River	River Flow	NO	NO	YES
Webb et al. (1999); Pizzuto et al. (1999); Mueller et al. (2014)	North America	Colorado River	Debris fan analysis	YES	NO	YES
Topping et al. (1999)	North America	Colorado River	Grain size evolution	YES	NO	YES
Smith (1999)	North America	Colorado River	Suspended Sediments	YES	NO	YES
Andrews et al. (1999); Wiele et al. (1999); Hazel et al. (1999); Schmidt et al. (1999)	North America	Colorado River	Sand bars	YES	NO	YES
Kearsley et al. (1999)	North America	Colorado River	Infrastructure	NO	NO	YES
Valdez et al. (1999)	North America	Colorado River	Biology	NO	NO	YES
Harpmann et al. (1999; Marzolf et al. (1999)	North America	Colorado River	Economy / Management	NO	NO	NO
Cook et al. (2009); Lamb et al. (2006)	North America	Colorado River; Colorado River, Snake River, Kohala region	Valley Formation	NO	NO	YES
Nester et al. (2007)	South America	Hyperarid Atacama Desert	River flow	YES	NO	YES
Sissakian and Jabbar (2009)	Middle East	22 gorges in Iraq	Valley Formation	NO	NO	NO
Waele et al. (2010)	Europe	Flumineddu River	River flow	NO	NO	YES
Zhang et al. (2020)	North America	Rainbow Canyon	Valley Formation	YES	YES	NO
Campagnolo et al. (2021)	South America	Perdizes River	Woody debris	NO	YES	YES
Mazzali et al. (2021)	South America	Boi River	Management	NO	NO	YES
Vasconcellos et al. (2021)	South America	Mampituba River	River Flow	NO	YES	NO

Thus, the present doctoral dissertation aims to identify the relevant parameters for characterizing mountain rivers. In addition, it seeks to perform a hydrogeomorphological characterization of a canyon river located in Southern Brazil, using the Boi River, where is located the Itaimbezinho canyon as a study area. The Itaimbezinho canyon is part of the most extensive canyon chain in South America, consisting of an important geological heritage. Several field surveys were performed to characterize the geomorphological units and grain size distribution presented in the canyon, transition, and floodplain landscapes. Furthermore, the resistance to flow was investigated to preliminary describe the flow conditions in canyon rivers.

1.2 Objectives

The present dissertation aims to characterize some hydrogeomorphological issues of a canyon river in Southern Brazil and discuss its geomorphic units and hydraulics in contrast to alluvial rivers' characteristics.

The dissertation presents the following specific objectives to achieve the general goal:

- Analyze the relevant parameters needed to characterize mountain rivers;
- Assess if rivers inserted in canyon landscapes present distinct geomorphic units by comparing them to those in floodplain landscapes;
- Assess the spatial variability of the grain size distribution in a canyon river;
- Establish a conceptual model to characterize geomorphologically canyon rivers;
- Assess the flow resistance in canyon rivers and their hydraulic geometry.

1.3 Document Organization

To achieve the objectives of the present dissertation, I developed a series of studies presented in chapters 2 to 4 in the format of manuscripts. The chapters are based on the following publications or submissions:

- Paixão, M.A., Kobiyama, M., 2019. Relevant parameters for characterizing mountain rivers. Brazilian Journal of Water Resources 24(10), 1-13. https://doi.org/10.1590/2318-0331.241920180115
- Paixão, M.A., Kobiyama, M., Mao, L., González Ávila, I., Takebayashi, H., Fujita, M., 2021. Geomorphological characterization of a canyon river in Southern Brazil. Journal of South American Earth Sciences, 1-31. (Submitted).
- Paixão, M.A., Kobiyama, M., 2021. Flow resistance in a canyon river: a case study of the Boi River in Southern Brazil. Journal of Hydrology, 1-27. (in progress)

Figure 1-1 presents a general view of the topics covered in each chapter and their relations. Next, a summary of each chapter and its contributions are presented.

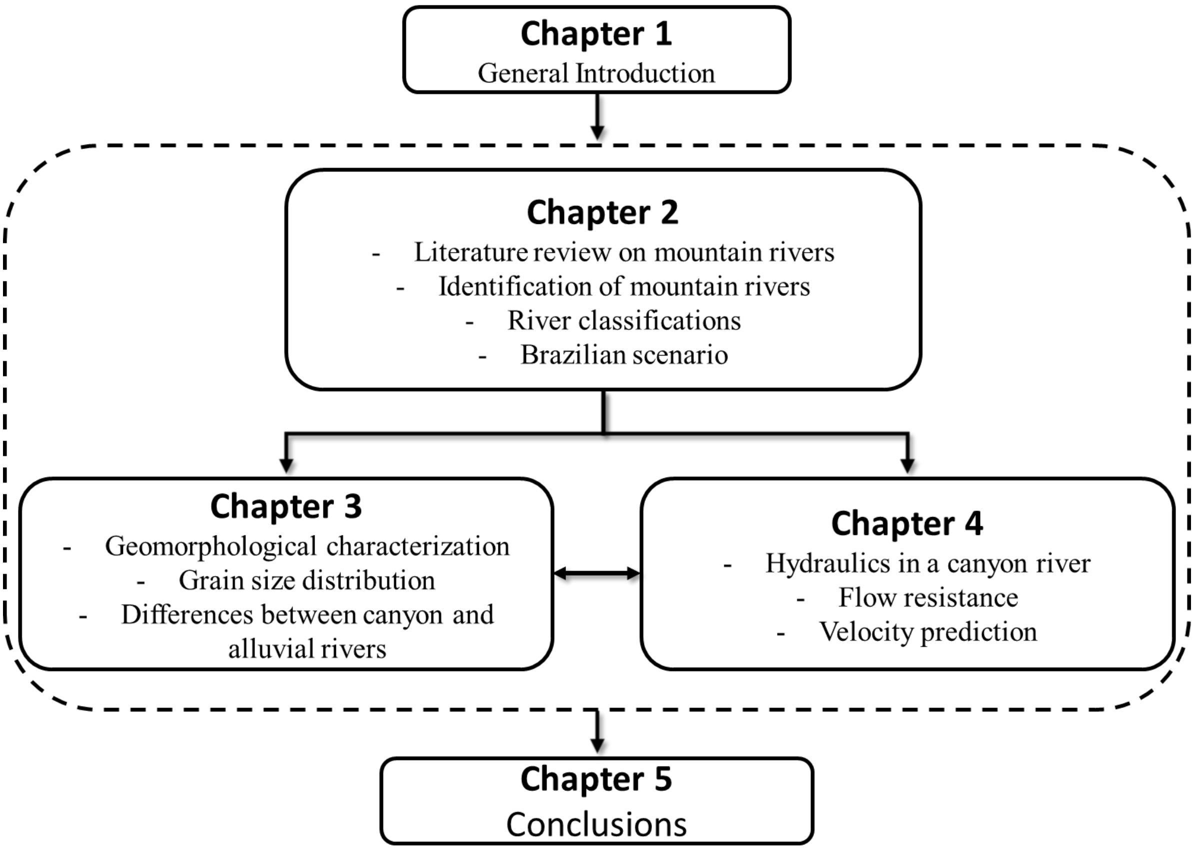

Figure 1-1 – Workflow organization

In Chapter 1, a general introduction is offered, presenting global aspects of the dissertation. In this chapter, I introduce the subject of this research and its objectives.

Chapter 2 consists of a literature review on mountain rivers in which a discussion about the hydrogeomorphological parameters needed for characterizing such environments. The study also includes the distinct approaches for classifying rivers and presents the Brazilian scenario on fluvial geomorphology research. This study evidenced the need for field surveys better to understand mountainous environments' fluvial dynamics and characterization.

Chapter 3 aims to identify the geomorphological characteristics of a canyon river, a specific case of a mountain river, using the Boi River as a study area. The Boi River has the Itaimbezinho Canyon, the most extensive canyon chain in South America. The field survey (topographic data, river width, river depth, floodplain width, channel slope, and grain size distribution) and computational modeling (geomorphic units' distribution) tries to identify the canyon's influence geomorphological characteristics of a river. Furthermore, it attempted to define the transition between canyon and alluvial rivers. It was considered three different reaches along the Boi River with the canyon, transition, and floodplain characteristics. In this chapter, a conceptual model was developed with geomorphological characterization. The results showed significant differences between canyon and alluvial rivers.

Chapter 4 presents a study of hydraulics in a canyon river, using the Boi River as the study area. In this study, the flow resistance was investigated in different reaches of the Boi River. The reaches were the same studied in Chapter 3. Flow velocity and discharge have been measured in the field. The downstream hydraulic geometry was verified in the Boi River using computational modeling. The results showed distinct behavior between portions of the river identified as a canyon river and parts identified as alluvial rivers. Furthermore, it was evaluated the velocity prediction in canyon rivers from flume-derived equations. The findings reinforce the hydrogeomorphological differences between canyon and alluvial rivers. The manuscript will be submitted to the Journal of Hydrology after the doctoral defense.

Chapter 5 presents a summary of the conclusions obtained during the dissertation and future perspectives on research related to the topics covered in this research. In addition, it gives suggestions for decision-makers in water resources management, especially in mountain environments.

The references are shown at the end of each chapter.

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CHAPTER 2

2. Relevant parameters for characterizing mountain rivers: a review

This chapter is based on the following paper published in the Brazilian Journal of Water Resources:

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Abstract

Mountain rivers are situated in a large portion of the terrestrial surface, especially in headwaters regions, and have been used for various purposes such as recreation, sporting activities, water resources, and hydroelectric power generation. However, the hydrogeomorphic characteristics of mountain rivers are not fully understood. In this context, the present paper aimed to identify relevant parameters for characterizing rivers in these environments based on a bibliographical review. It was identified which parameters have been used and how they have been used to characterize mountain rivers in distinct classifications. The most cited parameters were channel gradient, the relation between river width and depth, entrenchment ratio, discharge, sediment transport, and grain-size distribution. Also, the current situation related to researches in fluvial geomorphology in mountain rivers in Brazil was evaluated, and the strong need for field survey as the basis for the best understanding of mountain fluvial dynamics and characterization was verified.

Keywords: fluvial characterization, mountain environment, hydrogeomorphology.

2.1 Introduction

Mountain environments are presented in a large portion of continents and oceanic islands, being that in South America they represent up to 22% of its territory (Bridges, 1990).

Although there are several classifications to define what is a mountain (Fairbridge, 1968; King, 1967; Bates and Jackson, 1984; Price, 1991), it is not yet a consensus if they should be classified by esthetic standards or by morphological parameters such as height, altitude or shape. According to Faria (2005), it is convenient to classify the mountains by their height which can be defined as the vertical distance between their basis and summit and to consider the mountains as the environments whose height is more than 300 m.

As reported by Wohl (2010), mountain rivers show typical characteristics such as high slope, a high oscillation between the minimum and maximum discharges, high mobility of bedload sediments, countless transitions between sub and supercritical flow, limited supply of fine sediments, large variation in channel geometry associated to sediment supply, debris flow occurrences and high channel entrenchment ratio. Fryirs et al. (2007) commented that in mountain rivers, the water and sediment move quickly in the catchment, accomplishing hydrogeomorphic processes more extremely.

In Brazil, although mountain rivers have been used for different purposes (tourism, recreation, hydroelectric energy, etc.), there are still a few studies about them and their characteristics (for example, Faria and Marques, 1998; Faria, 2000; 2005; 2014). According to Kobiyama et al. (2006, 2018), the occupation and use of mountain catchments have been intensified. Such requests occur exactly where the hydrogeomorphic processes are more intense and still less studied.

Therefore, the objective of the present study was to evaluate the relevant parameters for characterizing mountain rivers, as well as dealing with their measurement, limitation, difficulties, and problems. Thus, it was sought to discuss the characterization of mountain rivers to the Brazilian community, which is still lacking in these studies.

2.2 River Classifications

Several authors have been proposing different approaches for classifying rivers: (i) channel orders, (ii) process domains, where the physical processes occurring in rivers are considered, (iii) fluvial channel patterns, (iv) interactions between channel and floodplain, (v) mobility and bed material, (vi) channel units, (vii) hierarchical classifications; and (viii) statistical classifications. The use of distinct classifications is conditioned basically with the analysis purpose, i.e., the degree of detail and the objective.

Classifications based on channel order (Horton, 1945; Strahler, 1957) or its magnitude (Shreve, 1966) offer little information about channel morphology. However, they emphasize the drainage network structure and describe the size and the relative location of channels in a catchment. Wohl (2000) commented that most mountain rivers do not have or have a few tributaries, being generally up to second order. However, some rivers in mountain environments in Brazil could be up to fourth order, in regions like Serra do Mar, Serra da Mantiqueira, Serra do Caparaó, and some regions of Atlantic Forest.

Classifications based on physical processes that occur in rivers (Schumm, 1977; Rosgen, 1994; Montgomery and Buffington, 1997, and so on) used to divide them into sediments' production or source, transfer or transport, deposition, or river response to sediment zones. Montgomery (1999) developed the concept of process domains, i.e., portions of the fluvial network characterized by a specific interrelated set of processes and disturbances, channel morphologies, and aquatic habitats that correspond approximately to sediment production, transport, and deposition zones. In addition, the classification of the river based on the process domains identifies fundamental geomorphic units in the landscape that structures the river behavior.

Another way is from pattern analysis of fluvial channels (Lane, 1957; Rosgen, 1994; Brierley and Fryirs, 2005), where the studies are based on continuity of determined pattern and deal with the factors (sediment size, bedload transport, roughness, width, and depth of channels) that change these patterns. The factors can also be slope, specific energy, the relation between width and depth, capacity, and competence of bedload material. The approaches derived from Schumm (1977) provide good conceptual models that assist in recognizing the channel morphology and their responses to disturbances in discharge and sediment supply and include morphologies presented in mountain rivers, such as Church (1992; 2006).

The interactions between channels and floodplains (Stevens et al., 1975) aimed to identify the controls of the physical and morphological processes both for rivers and plain. They are not associated with mountain rivers once their analyses focus on plains. This kind of classification aims to describe the long-term process in channels, especially the plain rivers.

When classifying rivers due to sediment mobility and bed material (Church, 2006; Buffington, 2012;), they are divided according to their substrate, if they are alluvial fans or gravel bedload channels. Montgomery et al. (1996) proposed that gravel bedload channels occur where the sediment transport capacity exceeds their supply. Meanwhile, alluvial rivers occur where the sediment supply corresponds to or exceeds the transport capacity. Benda (1990) commented that gravel bedload rivers could also occur in reaches with a debris flow occurrence and do not necessarily have fluvial characteristics. Church (2002; 2006) presented a refined scale for classifying bedload mobility defined in terms of Shields critical stress, where sediment size, transport regime, channel morphology, and stability are related. Whiting and Bradley (1993) proposed a classification for the mobility of headwaters rivers from mechanics equations, considering the potential loss of mass in the adjacent hillslope, the mode of transport and the channel competence for moving the deposited material, and if the sediment pulse is deposited in the river or not. This classification is particularly attractive because it is strongly based on processes and allows quantifying the disturbance risk to the fluvial system and their potential to respond to it.

Classifications based on channel units (Bisson et al., 1982; Montgomery and Buffington, 1997; Zimmermann and Church, 2001; Buffington et al., 2002, 2009) evaluate the morphological units encountered in reaches such as pools, bars, steps, and riffles. These units also form structures in blocks of large morphological reaches as step-pools, riffle-pools, and cascades.

Several studies tried to understand the hydraulics in these types of units as well as their physical and biological characteristics in steep channels (e.g., Grant et al., 1990; Zimmermann and Church, 2001; Halwas et al., 2005). Since they are characteristics observed in small reaches of the rivers, Montgomery and Buffington (1997) commented that these classifications are over-detailed for major applications in catchment scale. It causes some difficulties in investigating the mechanics of pluvial processes. However, they are essential concerning steep rivers (Moir et al., 2009), i.e., mountain rivers.

Considering hierarchical classifications (Frissell et al., 1986; Buffington et al., 2003; Church, 2006), the river network can be divided into homogeneous reaches based on channel patterns so that the morphology and channel conditions are evaluated in detail at different scales. The analysis is performed at the catchment level, acting in successive scales of physical and biological conditions, which allows a holistic approach. Historically, hierarchical classifications have been developed, emphasizing mountain rivers (Buffington and Montgomery, 2013). However, the process domains are still not well explained. Figure 2-1 shows a scheme of hierarchical classifications.

Furthermore, there is a statistical classification (Thompson et al., 2006) whose main objective is to predict morphological channel characteristics from spatial statistics for classifying reaches based on distinct bedload topographies. It is important to identify spatial patterns that could be replicated in channels with similar architectures in this case.

According to Buffington and Montgomery (2013), the use of one classification to the detriment of another can be related to advances in science and regional needs and the purpose or philosophy behind the classification. Hierarchical classifications are in vogue because they approach the need in holistic studies covering the whole catchment and physical and biological processes on different scales besides being developed for mountain rivers. However, a common mistake that river classifiers take is the indiscriminate use of some methods described by an author without an appropriate field survey that corroborate these arguments. As these hierarchical classifications were explicitly established for mountain rivers, the present study adopted them.

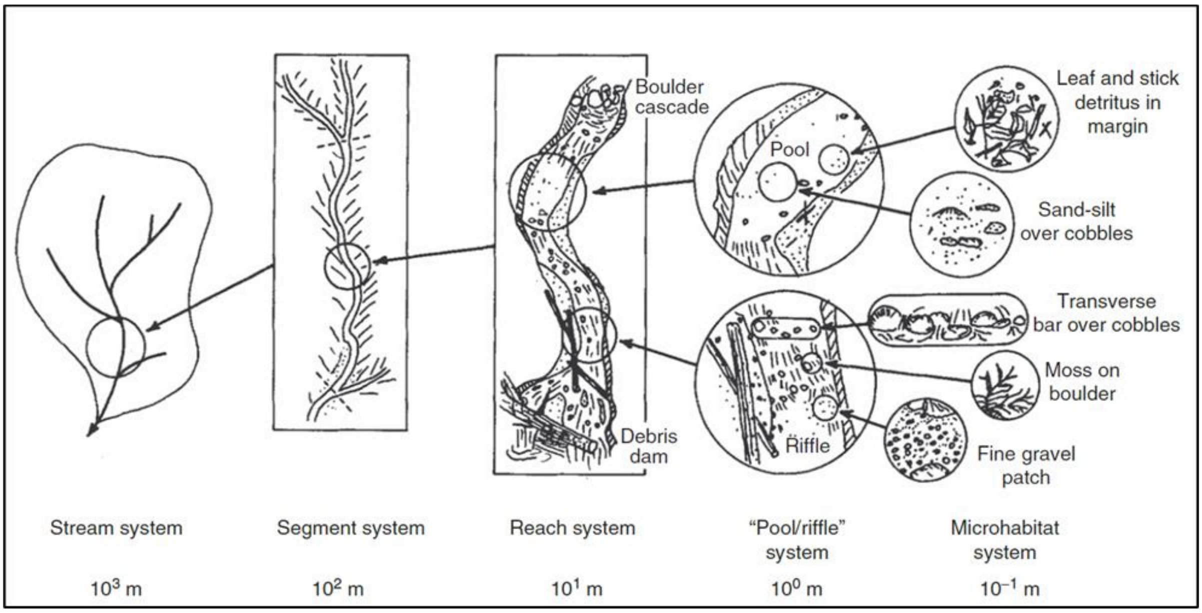

Figure 2-1 – Hierarchical classification of rivers (Source: Frissel et al., 1986)

2.3 Mountain Rivers

In her book entitled "Mountain Rivers Revisited", Wohl (2010) commented that the most consistent characteristic of mountain rivers might be their high slope. However, the author confirmed that this characteristic is strongly related to others such as limitation of channels resistant to erosion and hydraulically roughness associated with gravel bedload sediments, highly-turbulent flow with large variations between critical and supercritical flow, high spatio-temporal variability of bedload material, high longitudinal variation in channel geometry, high entrenchment ratio, among others.

Mountain rivers that are present in headwaters regions are subject to geomorphic alterations in time and space. According to Sklar and Dietrich (1998), these alterations include process transition from hillslope to channel and transitions from bedrock to gravel bedload or from gravel bedload to sand bedload.

Due to the fact that the river characteristics are not continuous in its extension and also that the river shows geomorphic alterations in time and space, it is very important to identify the places where these characteristics suffer from changes. In other words, a part of the river can be considered as mountainous meanwhile another as alluvial.

Lin and Oguchi (2009) evaluated longitudinal and transversal profiles in rivers over one mountainous catchment and demonstrated that topographic characteristics present different levels of organization between steeper and flatter regions. According to them, meanwhile, the global gradient of the catchment is determined by the longitudinal inclination; the transversal slope plays an important role in less steep areas, which evidences the need to evaluate the channel steepness in the field.

Ohmori and Shimazu (1994) analyzed different hazard types (debris flow, turbidity flow, and floods) in mountain rivers and their relations with geomorphic parameters. The authors reported that these different types could occur in distinct locations of channels, depending upon the channel steepness in a reach.

Buffington and Montgomery (2013) commented that because river classifications are extremely qualitative, the characterization of fluvial environments is still quite empirical. Thus, measuring mountain rivers remains still a challenging task.

Based on an analysis of different classifications, the most commonly used and most useful parameters related to rivers in mountain environments are identified (Table 1). The channel gradient, width, depth, entrenchment ratio, discharge, sediment load, and grain size are commonly used regardless of the type of river classification. Next, these relevant parameters will be discussed by considering mountain environments.

Table 2-1 – River classifications and commonly used parameters.

Classification	Main Authors	Common used parameters	Relation with Mountain Rivers
Channel order	Horton (1945) Strahler (1957)	Stream order; number of tributaries	Intermediate
Process domains	Schumm (1977) Rosgen (1994) Montgomery and Buffington (1997) Montgomery (1999) Brierley and Fryirs (2005)	Width, depth, channel gradient, type of terrain, entrenchment ratio, roughness	Strong
Channel patterns	Lane (1957) Leopold and Wolman (1957) Schumm (1977) Church (1992; 2006) Brierley and Fryirs (2005)	Geometric plain view, entrenchment ratio, channel gradient, sediment size, sediment load, riparian vegetation, roughness, sinuosity, width, depth	Strong
Channel – Floodplain Interactions	Melton (1936) Stevens et al. (1975) Nanson and Croke (1992) Beechie et al. (2006)	Width, depth, sinuosity, water quality (physical and chemical)	Weak
Sediment mobility and bed material	Gilbert (1917) Whiting and Bradley (1993) Montgomery et al. (1996) Dietrich et al. (2005) Church (2002; 2006) Bunte et al. (2010)	Channel substrate, capacity, competence, Shields critical stress, entrenchment ratio, sediment size, channel gradient, width, depth, sediment load, discharge, sediment connectivity, sediment transport (bedload or suspension)	Strong
Channel units	Bisson et al. (1982) Sullivan (1986) Grant et al. (1990) Montgomery and Buffington (1997) Zimmermann and Church (2001) Buffington et al. (2002) Buffington et al. (2009) Lave et al. (2010)	Channel substrate, capacity, competence, Shields critical stress, entrenchment ratio, sediment size, channel slope, width, depth, sediment load, discharge, occurrence of bars, steps, rifles and pools and their morphometric characteristics.	Strong
Hierarchical	Frissell et al.(1986) Paustian et al. (1992) Buffington et al. (2003) Church (2006)	Stream order, number of tributaries, width, depth, channel gradient, entrenchment ratio, roughness, channel substrate, capacity, competence, sediment size, sediment load, discharge, sediment connectivity, sediment	Strong

Classification	Main Authors	Common used parameters	Relation with Mountain Rivers
		transport (bedload or suspension), occurrence of bars, step, riffles, pools and their morphometric characteristics; presence, location and orientation of leaves and debris in margins	
Statistical	Thompson et al. (2006) Zimmermann et al. (2008)	Geometric plain view, entrenchment ratio, width, channel gradient, discharge	Intermediate

2.4 Relevant Parameters

2.4.1 Channel gradient

As mentioned above, the channel gradient is, probably, the most consistent parameter in the mountain rivers analysis (Wohl, 2010). It affects the hydraulic process of discharge and sediment transport and is related to other characteristics such as the occurrence of channel units and alteration in flow regime.

Moreover, the utilization of the unique value for channel gradient causes underestimating hydrogeomorphic processes in headwaters regions and overestimating the processes in floodplains. Therefore, the utilization of hierarchical classifications in different scales for characterizing mountain rivers is suggested.

Mountain rivers englobe transitions in channel patterns, i.e., the transitions between bedrock and gravel or between gravel and sand bed (Sklar and Dietrich, 1998). As sediment transport is related to channel gradient, one of the main proposals is to verify its condition where the patterns' changes occur. Wohl (1993) described in detail channel units characteristics and verified that in the gradients over 0.002 m/m, it can be possible to observe this kind of change in morphology. Several studies about channel gradient in mountain areas (Lenzi, 2001; Buckrell, 2007; Mao et al., 2010) demonstrated that the gradient in the mountains is usually with a magnitude of cm/m; meanwhile, floodplain environments with a magnitude of cm/km (LeFavour and Alsdorf, 2005).

The ways to measure channel gradient depend on the scale required in the analysis: river, segment, and reach of channel units; all demonstrated in Figure 2-1. For a river scale, remote sensing and geoprocessing from Digital Elevation Model (DEM) with good resolution (for example, 1:50,000) can be used. For a segment scale that has its magnitude of 10^2 m (Frissel et al., 1986), both DEM with appropriated resolution and topographic and topobathymetric data can be used.

An analysis of reach (10^1 m) and channel units (100 m) requires a field survey with a total station, differential GPS topographical level, and/or drones in order to obtain topographic and topobathymetric data (Figure 2-2a). According to Arroyo et al. (2010), the utilization of LiDAR (Light Detection and Ranging) allows obtaining information from the terrain with 50-cm resolution. In the case of the step-pool morphology analysis, the gradient value depends on the step approach. In other words, different ways to measure in the field generate different values of the gradient. For example, the measurement can be performed from the beginning of the upstream pool to the end of the downstream pool (α_{AD}) or from the upstream step to the downstream step (α_{BC}) (Figure 2-3).

Figure 2-2 – Field survey and measurement: (a) morphometric parameters by using a total station; and (b) discharge by using ADCP (Source: elaborated by the authors)

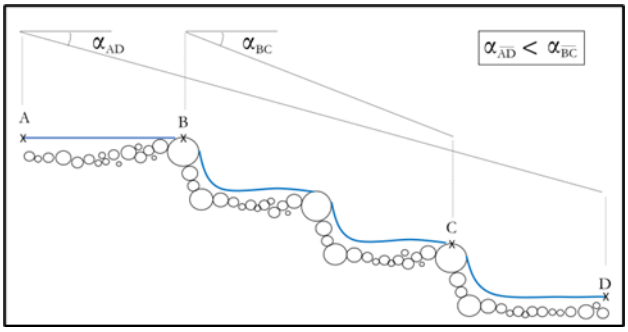

Figure 2-3 – Step-pool sequences with different gradients that can be obtained from the same channel unit

2.4.1 Relation between river width and depth

Morphometric parameters such as width and depth are commonly required to characterize mountain rivers, especially their width/depth relation. According to Rosgen (1994) Classification, the value of this relation must be lower than 12 for river types Aa+, A, B, F, and G, which indicate the mountain rivers in his classification due to channel slope and geometric plain view criteria. It should be here mentioned that the Rosgen Classification does not refer directly to mountain rivers, although the proposal index shows similarities that allow them to be classified in the previously mentioned classifications.

In general, these parameters are not easily obtained with remote sensing techniques. However, the river width can be measured with images from a reasonable number of pixels, once the pixel resolution may cause measurement errors. In mountain environments, the grid resolution from an image is more extensive than the river's dimensions, making the obtention of morphometric parameters from remote sensing techniques impossible. In this case, a field survey becomes indispensable.

Thus, the obtention of parameters as width and depth in reach scale should be performed by using a total station and a measuring tape. In this way, these parameters can be measured together with the channel gradient. Hence, the importance of hydrometry and topo-bathymetry in field surveys increases.

2.4.2 Entrenchment ratio

The entrenchment ratio of a river indicates how it is excavated in the landscape (Rosgen, 1994), i.e., how the river is limited laterally by banks and hillslopes. It is related to the vertical contention of rivers and allows making some inferences about the channel's adjacent area. The entrenchment ratio is determined by the relation between flood-prone areas and channel width. The flood-prone area is estimated as the width measurement for the river elevation corresponding to the double of maximum river depth for a specific cross-section.

Therefore, obtaining the entrenchment ratio requires knowing the river depth and the flood-prone area in the study site. These data come from a detailed field survey by using total station and measuring tapes. If the mean depth is known and a DEM with good resolution is available, the measurement of the flood-prone area could be estimated by Geographical Information System (GIS) techniques.

Rosgen (1994) showed various examples of the typical entrenchment ratio. Thereby, this parameter can be estimated from a comparison between typical values showed in Rosgen analysis and study site, emphasizing that mountain rivers should be classified as Aa+, A, B, F, or G. On the other hand, non-mountain rivers present high values of this parameter. It means that they do not have significant lateral control of the margins and banks, allowing the large spread of channels and the connection among rivers, lakes, and meanders during flood events.

2.4.3 Discharge

It is almost impossible to perform traditional methods for measuring discharge in mountain rivers during flood events due to its high velocity and sediment mobility (Chen, 2013). In addition, discharges during floods could change very quickly in a short time, making it indispensable to perform the measure as fast as possible. This temporal variation must be a characteristic of mountain rivers.

In mountain rivers, the time of concentration was very short, of magnitude from a few minutes to one hour, which still makes it challenging to perform systematical discharge measurements to cover all the flood events. Because of its short time of concentration, the floods in mountain rivers are considered flash floods (Kobiyama and Goerl, 2007). Furthermore, as the response time is very short, the field surveys have been frequently combined with extreme rainfalls. This fact also increases the difficulty in measurements.

Therefore, the use of ADCP (Acoustic Doppler Current Profiler) (Figure 2-2b) is strongly recommended to measure discharges in mountain rivers. This use allows obtaining the relation between velocities and areas more reliable than traditional methods during flood events. In addition, the use of ADCP allows performing the measurement quickly than conventional methods (Gamarro, 2012). However, mountain rivers used to present low depths, which can cause some difficulties in performing the measurement. Therefore, it is necessary to look for an appropriate transect that at least has the minimum depth for the ADCP use and also provides security for the field workers.

It is important to highlight that for non-mountain rivers, it is not difficult to apply the traditional methods with a propeller current meter or ADCP, as described in the technical report of large rivers discharge measurements (ANA, 2009). Also, satellite images can be used to estimate discharges at a cross-section of an alluvial river. For example, LeFavour and Alsdorf (2005) demonstrated the possibility of estimating discharges in a river belonging to the Amazon region with remote sensing. The authors commented that bathymetry was the unique parameter that could not be obtained by image. However, due to a very large river whose other parameters could be estimated, the bathymetry could be neglected since the calibration process used a well-known river gauge station.

In this way, it is highlighted that different ways obtain water discharge measurements in mountain and alluvial rivers. Therefore, the present study emphasizes that both methods and temporal changes are important items in river classification, once mountain and alluvial rivers differ consistently in these subjects.

2.4.4 Sediment Load

The sediment transport in mountain rivers is one of the most uncertain parameters in their values. According to Brardinoni et al. (2015), the sediment dynamics in mountain rivers depend on a series of complex interactions among river discharge, activation of sediment sources from different types, and river morphodynamics.

Sediment load has large uncertainty associated with its estimative (Buffington and Montgomery, 2013), once there is a lack of direct observations in the field with appropriate quality and quantity that could allow the development of physically-based sediment models (Brardinoni et al., 2015)

Montgomery et al. (1996) followed the hypothesis of Gilbert (1917) in which gravel bedload rivers occur where the transport capacity exceeds the sediment supply; meanwhile, alluvial rivers occur where the sediment supply corresponds to or exceeds the transport capacity. Schumm (1977) commented that the channel patterns and their stability are influenced by sediment size and transport mode (of suspension, mixed with bedload, or bedload). In the case of the suspended sediment load, there are several attempts to estimate their quantity by using turbidity sensors (Sari et al., 2015, 2017).

In mountain rivers that used to present low suspension sediment load, bedload discharge is the main way of sediment transport (Montgomery et al., 1996). According to Merten and

Minella (2014), without a measurement of bedload sediment discharge, it is recommended to use Einstein or Colby equations or a supposition that a certain percentage of the suspension represents the bedload discharge. In Brazil, it is very common to consider 10% of the total sediment transport as bedload (Carvalho et al., 2000). By monitoring a river in a semi-arid region in Brazil, Cantalice et al. (2013) showed that the percentage of bedload to suspended sediment load varied from 4 to 12.72%. Although Macedo et al. (2017) investigated the bedload transport, their study area was a floodplain area without mountain environments.

Understanding the sediment dynamics and sediment load transport is a fundamental task for classifying rivers as mountain rivers. However, it is pretty challenging to observe the transformation from mountain to the alluvial river, which needs to improve field surveys in mountain environments. Moreover, even it could be complex and time-consuming, it is necessary to estimate the amount of sediment load. Thus, the need for field hydrometry increases.

2.4.5 Sediment size

The spatial and temporal distribution of the sediments can strongly affect the water discharges conditions, the turbulence structures, and the sediment transport rates (Bathurst, 1987; Rickmenmann, 2001; Dey et al., 2011; Tsakiris et al., 2014). Large sediments strongly increase the spatial variability of discharge and turbulence intensities in a reach scale (Dey et al., 2011; Ozgoren et al., 2013).

Due to its great importance in the water flow dynamics in rivers, the sediments size distribution should be described to demonstrate its characteristics as accurate as possible. The sediment size is used, for example, to estimate hydraulic characteristics for incipient sediment movement (Mao and Lenzi, 2007). There are some parameters of interest, as D_{16}, D_{50}, D_{84}, and D_{90}.

There is a diversity in sediment measurement methods in rivers (Church et al., 1987; ISO, 1992; Ramos, 1996); however, a few papers provide information on bedload material sampling in small mountain catchments (Bunte and Abt, 2001). Bevenger and King (1995) proposed a counting sediment procedure in which the grains are sampled from a cross-section from bank to bank to describe such size distribution in mountain rivers.

Fang et al. (2017) commented that large sediments could promote changes in the field of discharges and cause flow deacceleration, corridor and vortex formation, internal and external turbulence, and redistribution of shear stress. When large sediments are neglected, these alterations as well as sediment transport ratio may be underestimated. In this way, the importance of the spatial distribution of large sediments, i.e., the maximum sediment sizes, or D_{100} must be emphasized

Hence, it is evident that the need to perform a field survey to describe the sediment size appropriately in rivers. Mao et al. (2010) verified sediment size distribution through a field survey and evaluated the river competence in an Italian Alps catchment. They utilized markers in a wide range of sediment sizes that allowed them to infer possible discharges capable of transporting these sediments. Buckrell (2015) evaluated differences in sediment size distribution for pools and riffles sequences and reported that they are considered distinct in sediment size, which requires further investigation in situ. In addition, different technologies could be used for estimating the sediment size, such as drone images processing (Mu et al., 2018) or satellite images (Casado et al., 2015). Mu et al. (2018) performed machine learning to identify morphological characteristics of the sediments. Although this technology has been advancing very rapidly, field survey, i.e., field hydrometry, is still necessary for obtaining primary data.

2.5 Brazilian Scenario

The development and occupation have been increasing significantly in Brazilian mountain regions (Kobiyama et al., 2018). According to Hewitt (2004), the growing use of mountain areas has been rising the hazard for hydrologically-extreme events due to pressure for development and environmental changes.

Mountain environments have been served as an alternative for water supply from large rivers, that water quality has now deteriorated on its quality (Paixão et al., 2017). Such a situation stimulates public agencies to build up capitation, treatment, and feed water infrastructure in these regions.

In addition, mountain regions have been increasingly sought after and exploited for recreation and ecotourism activities. Data from National Parks and Conservation Units Visitors showed that, in Federal areas, the total number of visitors grew from 3 million in 2007 to more than 8 million in 2016 (IBAMA, 2016). An expressive number of federal conservation areas are located in mountain regions, for examples, Aparados da Serra, Serra Geral, Chapada dos Guimarães and Itatiaia National Parks.

As exploitation and occupation of mountain environments have been rising in Brazil and the studies referred to these areas still are scarce, it is essential to incentivize basic studies about mountain rivers characterization. Such studies will subsidize the comprehension of the water and sediment dynamics in these environments.

Faria (2000) evaluated the influence of vegetation on fluvial processes in first-order catchments, highlighted that woody debris (tree trunks, branches, and leaves) interfere in water flow in diverse ways. He also commented that the sediment delivery in these catchments occurs in pulses when such structures are destroyed. Assessing geomorphic responses in first-order fluvial channels, Faria (2014) reported that sediment transport presents very differentiated dynamics compared with larger rivers. Therefore, the first-order channels demand more studies.

Using principal component analysis and cluster analysis, Sodré et al. (2007) performed multivariate analysis to describe and classify morphometric parameters in catchments in Alto Jequitaí-MG. The analyzed parameters were altimetry, terrain slope, hillslope curvature, contribution area, and catchment perimeter. In addition, the authors segmented catchments according to their similarity patterns, evidencing that spatial patterns reflect the similar dynamics among them.

Silveira and Ramos (2007) carried out a spatial analysis of a mountain catchment's environmental parameters and hydrological behavior at Serra dos Órgãos-RJ. For this analysis, the authors used the Ground Penetration Radar (GPR) to evaluate the distribution and transition of soil horizons in the field, investigated the sediment size distribution at distinct locations in the catchment, and used fluviometric data with 30 minutes of temporal resolution. The field survey allowed the determination of landscape development patterns for different lithological units in the catchment, indicating factors that act as controllers in the relation between rainfall and discharge in this mountain region.

Olszevski et al. (2011) evaluated the morphology and the hydrological aspects by using morphometric characteristics of the terrain and the drainage network to predict the hydrological behavior. Lopes (2012) used topographic attributes to establish the relationship between topography and discharge in the Altíssimo Rio Negro catchment (PR/SC). Such attributes were obtained from GIS processing and field surveys for discharge measurements.

Telles et al. (2016) carried out automatic calibration of the hydrodynamic simulator by using direct and reverse problems, whose objective was to minimize the difference between experimental data referred to river level and simulated values obtained in the direct problem. The authors utilized data with 15 minutes of temporal resolution and got satisfactory results. However, the authors stated that the results could be better if they had more parameters in the analysis, i.e., if they had a more detailed description of hydrogeomorphic processes in mountain environments. One of the main propositions of Telles et al. (2016) was to consider the roughness variability along the channel to make the prediction more realistic to physical characteristics observed in terrain. It indirectly means that reach scale needs to be better described for a good representation of its processes.

Studies related to modeling and water quality have been increasing in Brazil. For example, von Sperling (2007) recommended using nine parameters (temperature, pH, dissolved oxygen, BOD, thermotolerant coliforms, total nitrogen, total phosphor, total solids, and turbidity) for evaluating the water quality index.

Girardi et al. (2016) evaluated the changes in water quality during rainfall events in the Cubatão do Sul river catchment in Santa Catarina state. The study was assessed two sub-catchments, being one of them predominantly mountain environments. It was treated temperature, electrical conductivity, turbidity, pH, ammonium ion, and dissolved oxygen. The authors observed that the catchment is influenced by discharges with short return periods. The water quality keeps a uniform behavior during dry and rainy periods in the mountain sub-catchment, which is mainly preserved.

Rodrigues et al. (2012) tried to estimate dispersion pollutant parameters in mountain rivers by using the Luus-Jaakola algorithm. They commented that the dispersion of pollutants in natural streams had been based on classical experiments that consider a Gaussian distribution of one substance concentration. However, it is not verified in mountain environments. Thus, when using the advection-dispersion model, they had a good estimative to calculate the transport of a conservative substance.

Hence, it is observed that studies on mountain rivers are still few when compared with alluvial rivers and floodplains in Brazil. Such a situation probably implies that researchers are more interested in larger catchments and large rivers because of the hydroelectric energy generation. The large portions facilitate studies using remote sensing. That is why, to understand mountain rivers better, Brazilian researchers should add efforts on field surveys activities, carrying out in situ measurements, since the Brazilian society has increasingly used mountain rivers.

2.6 Conclusions

Due to the increasing use of mountain environments in Brazil, it is suggested that river classifications must be performed by considering their uses for different purposes.

For characterizing mountain rivers, it is proposed to use hierarchical classifications where rivers are evaluated on different scales of analysis (river, segment, reach, channel units, etc.) to analyze the relevant parameters for its characterization. According to Wohl (2010), the most permanent parameter in the analysis of mountain rivers is the channel gradient. Thus, in the impossibility of a complete characterization of a river, channel gradient may offer to subside for preliminary characterization of mountain rivers. It is emphasized that for a full estimative, field observations are necessary, which requires financial expenditure and time.

Identifying the minimum relevant parameters needed for characterizing mountain rivers is a demand both for the scientific community and for Brazil, as the country has been intensifying the use and occupation of mountain environments, and there is a lack of studies in such settings. Thus, based on the literature review, it was observed that the most utilized parameters for characterizing mountain rivers are: channel gradient, discharge, the relation between river width and depth, entrenchment ratio, sediment load, and sediment size.

Although some parameters can be measured with geoprocessing techniques, most of them should be measured in situ. Therefore, it strongly indicates the importance of performing hydrometry, topography, and topobathymetry in the field survey.

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CHAPTER 3

3. Geomorphological characterization of a canyon river in Southern Brazil

This chapter is based on the following manuscript submitted to the Journal of South American Earth Sciences:

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Abstract

Canyon rivers are a particular case of mountain rivers in which canyons influence geomorphological characteristics of rivers, being located inside or close to the canyon landscape. Although several studies analyzed formation, flow structure, and sediment transport in these environments, there is still a lack of knowledge to define the extension of a canyon river and its transition to alluvial rivers. Thus, the present study aimed to develop a conceptual model based on the grain size distribution to identify the canyon influence on river characteristics and define the transition to alluvial rivers. We performed a field survey (river width, depth, floodplain width, gradient, and grain size distribution), and conduct a cluster analysis in three reaches (canyon, transition, and floodplain landscapes) along the Boi River, Itaimbezinho Canyon, southern Brazil. The results show that canyon and transition landscapes present similarities, whereas the floodplain landscape differs in terms of geomorphological characteristics and critical shear stress for sediment transport. The findings also show that the canyon influence on rivers decreases upstream to downstream, identifying, through grain size distribution, the region where this influence is absent. The conceptual model proposed in this study can help characterize and classify canyon rivers for environmental studies and river management purposes.

Keywords: canyon river, geomorphometry, grain size distribution, geomorphic units

3.1 Introduction

Rivers have been classified using different approaches depending on the objectives of the analysis. They can be classified by channel order (Horton, 1945; Strahler, 1957), process domains (Schumm, 1977; Montgomery and Buffington, 1997), fluvial channel patterns (Brierley and Fryirs, 2005), interactions between channel and floodplain (Stevens et al., 1975), mobility and bed material (Church, 2006; Buffington, 2012), channel units (Zimmermann and Church, 2002; Buffington et al., 2009), hierarchical classifications (Buffington et al., 2003; Church, 2006), statistical classifications (Thompson et al., 2006), and so on. Although there are several ways for classifying rivers, it is essential to know what type of river is the subject of the analysis for landscape evolution and river management purposes.

Mountain rivers, for example, differ from alluvial rivers in terms of higher slope, higher spatio-temporal variability of bed material and channel geometry, and higher entrenchment ratio (Wohl, 2010; Vasconcellos et al., 2021). Also, their transport capacity generally exceeds the sediment supply (Montgomery et al., 1996), while in alluvial rivers, the sediment supply corresponds to or exceeds the transport capacity. Mountain rivers carved on canyons are particularly difficult to study in terms of first surveys, morphological changes, sediment transport processes and are thus less known than alluvial systems.

Zhang et al. (2020) applied a moving-boundary model for evaluating river incision on bedrock in the Rainbow Canyon. They provided a template to predict long-term canyons incision, sidewall erosion, knickpoint erosion, and canyon extension in direction to upstream. By analyzing the possibility of springs cutting bedrock canyons, Lamb et al. (2006) concluded that, along with fluvial incision, seepage could contribute to shaping amphitheater-headed valleys. Thus, their works advanced the knowledge of valley formation from the viewpoint of headwaters.

Mueller et al. (2014) evaluated the influence of controlled floods on fine sediment storage by canyons. They showed that floods with short return periods could rebuild sandbars in debris fan areas. Furthermore, the authors reported that controlled floods might not solve reduced sediment supply conditions in the basin area, which is a crucial characteristic of mountain and canyon rivers. Sissakian and Jabbar (2009) revealed the morphometry and genesis of the main gorges in the Middle East. They highlighted essential parameters to measure for classifying canyon rivers concerning morphology, such as width, depth, width/depth ratio, and entrenchment ratio. Venditti et al. (2014) and Gasparini (2014) analyzed the flow structure in canyon rivers, showing that water velocity profiles do not follow the logarithmic pattern. Instead, high velocities were observed close to the bed, facilitating sediment transport by increasing shear stress in this region of the flow structure.

The size of sediments in the alluvial layer is important to understand bedrock erosion in bedrock-alluvial rivers as grains can erode the bedrock when transported, but protect it if the alluvial layer is tick and coarse enough. Chatanantavet et al. (2010) created a physically-based model of downstream fining in bedrock streams with lateral input from hillslopes. Their results showed that abrasion and selective sorting, which transport preferentially small-sized sediments, may play important roles and be equally important in generating downstream fining. Hodge and Hoey (2012) reported that large sediments in bedrock rivers inhibit incision by saltation and that a relation between bedrock exposure and relative sediment flux is necessary for better prediction. They commented that theoretical predictions contradict laboratory experiments. They also described a continuum relation between bedrock exposure and sediment flux that is most applicable and depends on the channel slope, roughness, and shear stress that exerts control in grain entrainment from bedrock to floodplains.

In this context, the present study aims to tackle the following issues: a) explore the extent to which canyons influence river characteristics; b) investigate the kind of geomorphic features compound a canyon river; c) explore the influence of canyon on grain size distribution along a river reach. To this end, we performed topographical field surveys, and we applied the Geomorphic Unit Tool - GUT (Wheaton et al., 2015) in three reaches along the Boi River, located in the Itaimbezinho Canyon, southern Brazil. There are several methods to survey, characterize, and classify the physical habitats of river systems (Belletti et al., 2017). As they generally need field surveys, the delineation of geomorphic units suffers from low accuracy due to observer subjectivity (Bangen et al., 2017). To avoid this issue, here we used the automated procedure of geomorphic units' delineation from high-resolution topographic datasets using a hierarchical classification adapted from Wheaton et al. (2015).

The analyses of these ensemble factors allowed discussing the similarity and difference of three different reaches characterized as a canyon, transition, and floodplain landscapes. Based on the obtained results, we propose one model of canyon rivers relating to geomorphic characteristics of rivers.

3.2 Materials and Methods

3.2.1 Study area

The study area is the Boi River basin (128 km^2), located along the border between the states of Rio Grande do Sul and Santa Catarina in southern Brazil. It is a typical mountain landscape with a canyon situated within the Aparados da Serra National Park (Figure *3-1*). The hillslopes are very steep, with altitude ranging from 1012 to 85 m a.s.l. with vigorous embedded valleys and canyons (Paixão et al., 2021). The region of the Boi River basin is part of the most extensive canyon chain in South America.

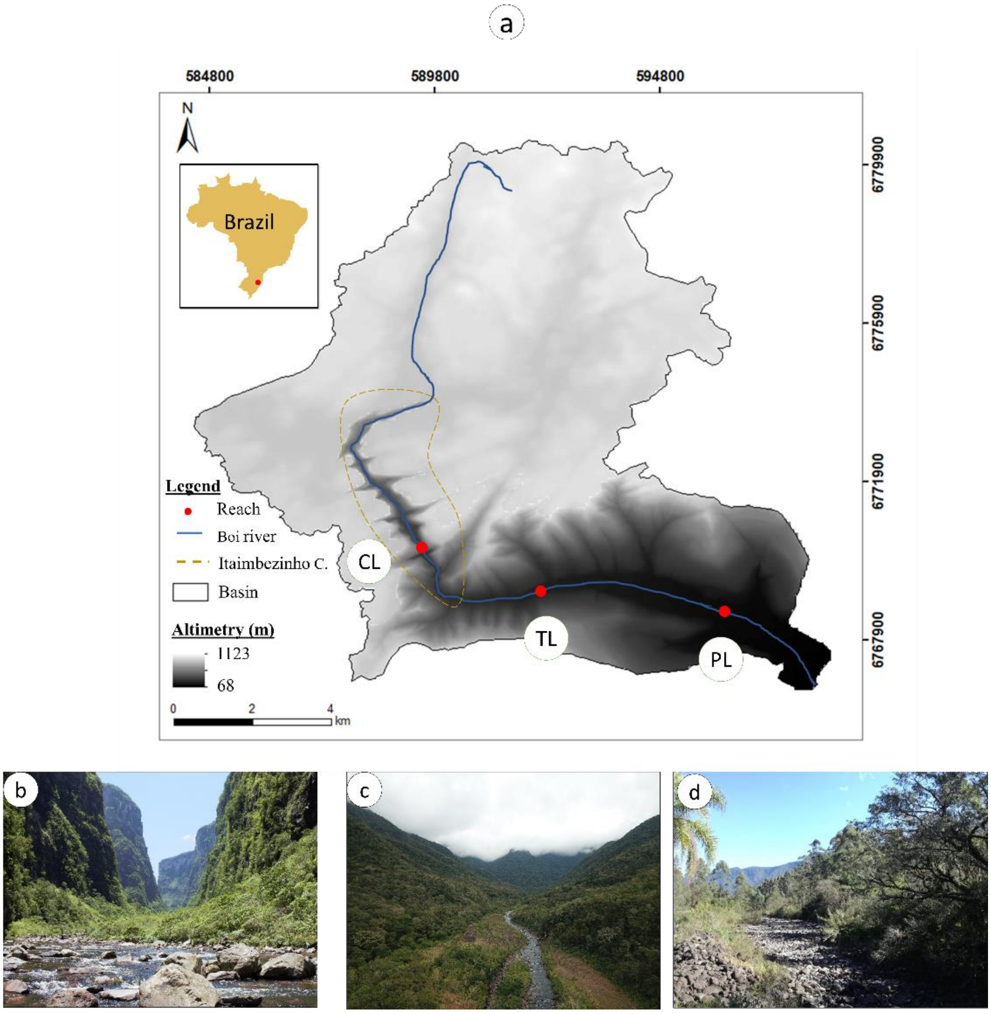

Figure 3-1 – Study area and selected reaches: a) Boi River Basin, b) canyon landscape (CL) reach, c) transition landscape (TL) reach, and d) floodplain landscape (FL) reach.

The Itaimbezinho canyon, to which the Boi River belongs, is around 5.8 km long and 500 m deep. The basin landscape character is the abrupt cut of the relief of the plateau of the Serra Geral Formation (predominantly basalt). Such geological formation dates back to the Gondwana rupture and the South Atlantic formation. According to the Köppen-Geiger classification, portions of the basin located upstream of the canyon are classified as Cfb (temperate oceanic climate). In contrast, portions downstream are classified as Cfa (humid subtropical climate). The study region presents well-distributed precipitation along the year with an annual mean of 1800 mm.

Due to its characteristics, there are efforts to promote environmental conservation and ecotourism in the region (Mazzalli et al., 2021). The study area is partially inserted in the Aparados da Serra National Park which has an ecotourism infrastructure with marked trails and accessible with accredited guides. Furthermore, a local community has been trying to establish a geopark in the area.

Here we focused on three reaches approximately 100 m long, located at different locations along the Boi River for characterizing the river geomorphology:

i) The first reach is deeply incised on bedrock and features the typical canyon landscape (CL). It represents the end of the Rio do Boi trail, entirely inside the Itaimbezinho canyon (Figure *3-1*b). Upstream from this reach the access is restricted by the National Park.

ii) The second reach has a typical mountain environment, referred to as a transition landscape (TL). The reach is within an entrenched valley with steep hillslopes (Figure *3-1*c) and represents a morphological transition between the canyon landscape and the floodplain landscape.

iii) The third reach is located downstream of the second reach, in the floodplain area (PL) (Figure *3-1*d). The reach is very close to the National Park limits and represents the area where the river becomes much wider in an alluvial fan.

All reaches feature geomorphic units such as bars, glide-runs, banks, and pools sequences and present distinct gradient and valley shapes. Such conditions allowed us to identify three representative reaches for the different portions of the Boi River basin to conduct this study. The CL, TL, and PL reach feature mean channel slope (S) of to 0.03, 0.016, and 0.010 m/m, respectively.

3.2.2 Topobatimetry data and DEM Generation

We obtained topobatimetric data during a field survey using a total station and an RTK-GPS device. As the GPS signal was weak in the study area, especially in close proximity and inside the Itaimbezinho canyon, the use of a total station was necessary for the complete analysis and coordinates' corrections. We conducted the field surveys during low-flow periods.

For each reach, ten equidistant cross-sections were surveyed. The topographic data was processed in ArcGIS® using the TopoToRaster tool. This process generated a Digital Elevation Model (DEM) with a resolution of 0.10 m for each reach. Such DEM resolution allows performing a consistent morphological analysis.

3.2.3 Parameters Measurement

At each reach (CL, TL, and PL), on the ten surveyed cross-sections we measured geomorphic features such as bankfull width (*W*), depth (*D*), channel slope (*S*), and floodplain width (*FW*). The water edge was identified and surveyed too. Lately, the river width (*W*) was measured directly from the generated DEM data related to the cross-sections (Figure 3-2). The water depth (*D*) was measured from the DEM data, considering the difference between the waterline and the thalweg altimetry. The channel slope (*S*) was measured for each cross-section individually from the DEM data. The floodplain width (*FW*) was measured using remote sensing techniques based on the Google Earth satellite images of the historic flood that occurred in 2007. The flood that took place in 2007 is one of the most significant extreme events ever registered in the basin area (Paixão et al., 2021). We considered that *FW* was the maximum observed in the satellite images. These shreds of evidence were recorded by satellite images and then measured by GIS tools.

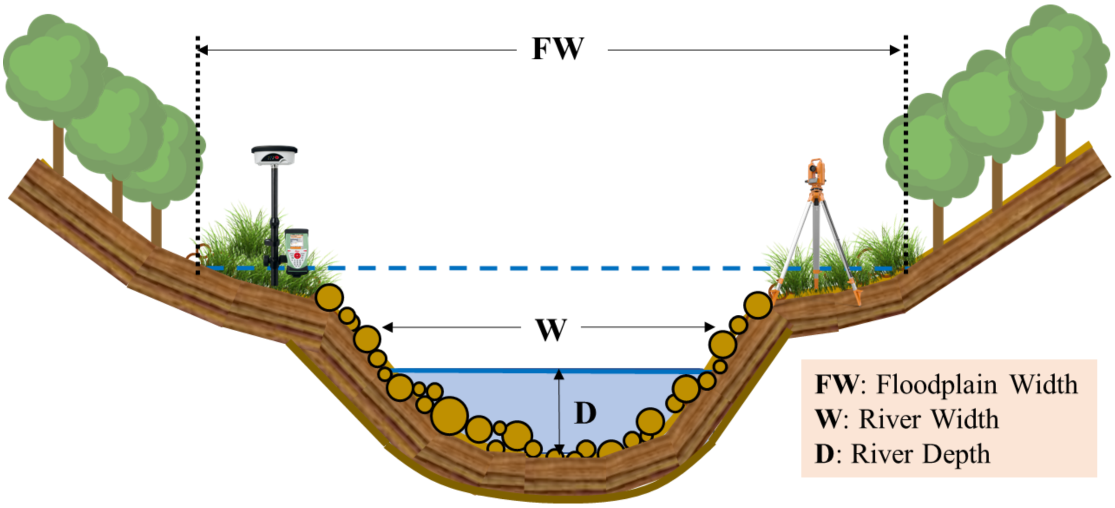

Figure 3-2 – Scheme of parameters' measurements

3.2.4 Cluster Analysis

Geomorphic patterns of the cross-sections in the CL, TL, and PL reaches were evaluated in terms of their similarity level through cluster analysis. Cluster analysis is recommended to delineate homogeneous regions, being the primary objective of finding subgroups or exploring common patterns within a larger group (Smoliński et al., 2002; Dogulu and Kentel, 2017). Reach classification was conducted using Ward's Method hierarchical cluster algorithm. Kuiper and Fischer (1975) showed that such a method presents some advantages over other clustering methods (i.e., Average Linkage) besides be more discriminative, forming more compact clusters, and being less sensitive to outliers. Ward's Method has been largely used for environmental assessments (i.e., Zolfaghari et al., 2019; Byrne et al., 2019). Ward's Method minimizes within-clusters variance and maximizes between-cluster variance. The variance between the cross-sections was based on the Euclidean Distance. As the Euclidean Distance is not affected by the addition of new objects but by differences in scale (Almeida et al., 2007), the input parameters were previously normalized to reduce scale effects.

There are some concerns in the literature about the use of clusterings, such as selection of the variables and features to cluster upon (Andrews and McNicholas, 2014), data scaling

(Tanioka and Yadohisa, 2012), and different types of data (Gan et al., 2007). To avoid biased cluster analysis due to inserting correlated parameters, we decided to use the parameters directly measured during the field surveys or obtained by the satellite images. For this reason, we considered only *W*, *D*, *FW*, and *S* in the cluster analysis. Furthermore, it was applied a normalization by maximum values of each parameter to reduce the scale effect.

The representativeness of the cross-sections in the reach was a significant concern about the analysis. Somehow, the proximity between two cross-sections may bias the results of cluster analysis. The resulting dendrogram must show the degrees of differences/similarities among the individual sites to assess this situation.

3.2.5 Geomorphic Patterns

Fryiris and Brierley (2004) stated that geomorphic units represent pieces of the mosaic that represent river morphology. Thereby, it is the result of the interactions between water flow and sediment transport. If geomorphic patterns are different between the cross-sections, the reaches may present other geomorphic units' combinations for implying such a situation. Thus, we decided to use the Geomorphic Unit Tool – GUT (Wheaton et al., 2015) to verify differences and similitudes among the geomorphic patterns in the three reaches. The GUT is four-tiered hierarchical taxonomy in which the geomorphic units are differentiated by the flow stage to the channel bed, shape, morphology type, and subcategories of sedimentological and vegetative characteristics. Tier 1 identifies the inundation surface of main stream floods. It helps identify the geomorphic unit, broadening scale controls on reach types, valley setting, and a natural capacity for adjustment. Tier 2 determines the shape (concavity, convexity, or planar). Tier 3 identifies the morphological characteristics, and Tier 4 identifies subcategories about some adjectives like roughness and vegetation association. The further into the tiered system, the more reliable the GUT results become (i.e., Belletti et al., 2017). Therefore, the topographic definition is fundamental to improve the GUT analysis.

We conducted a supervised automated procedure to classify the geomorphic units in the three considered reaches on applying the GUT. In other words, we performed the automated process described by Wheaton et al. (2015) under observer checking.

3.2.6 Sediment Size Survey

Sediment size was surveyed on each reach using the zig-zag pebble-count procedure (Bevenger and King, 1995) and measuring 100 clasts per reach. Appendix A shows a scheme of performed measurements. The clasts were sampled in the armoring, disregarding the sedimentation thickness. Alterations in the Boi River are not allowed as it is a conservation area. As fine sediments are rarely present in the study reaches, only sediments larger than 1 mm were measured.

The measurement for each pebble followed the description of Bunte and Abt (2001), i.e., the three diameters (*a*-, *b*-, and *c*-axises) were measured and computed. Then, the nominal diameter was calculated for each sediment as follows:

$$d_n = (a.b.c)^{\frac{1}{3}} \qquad (3.1)$$

where d_n is the nominal diameter in mm, a is the largest diameter in mm, b is the intermediate diameter in mm, and c is the smallest diameter in mm.

Lately, from the computation of the nominal diameter, the grain size distribution curves for all reaches were analyzed, which permitted the discussion of the Boi River's competence to transport sediments, especially concerning large sediments.

3.3 Results and Discussion

3.3.1 *DEM data and measured parameters*

Figure 4 shows the DEM data, the waterline, ten cross-sections per reach, and the surveyed points created by processing topobatimetry data obtained during the field survey.

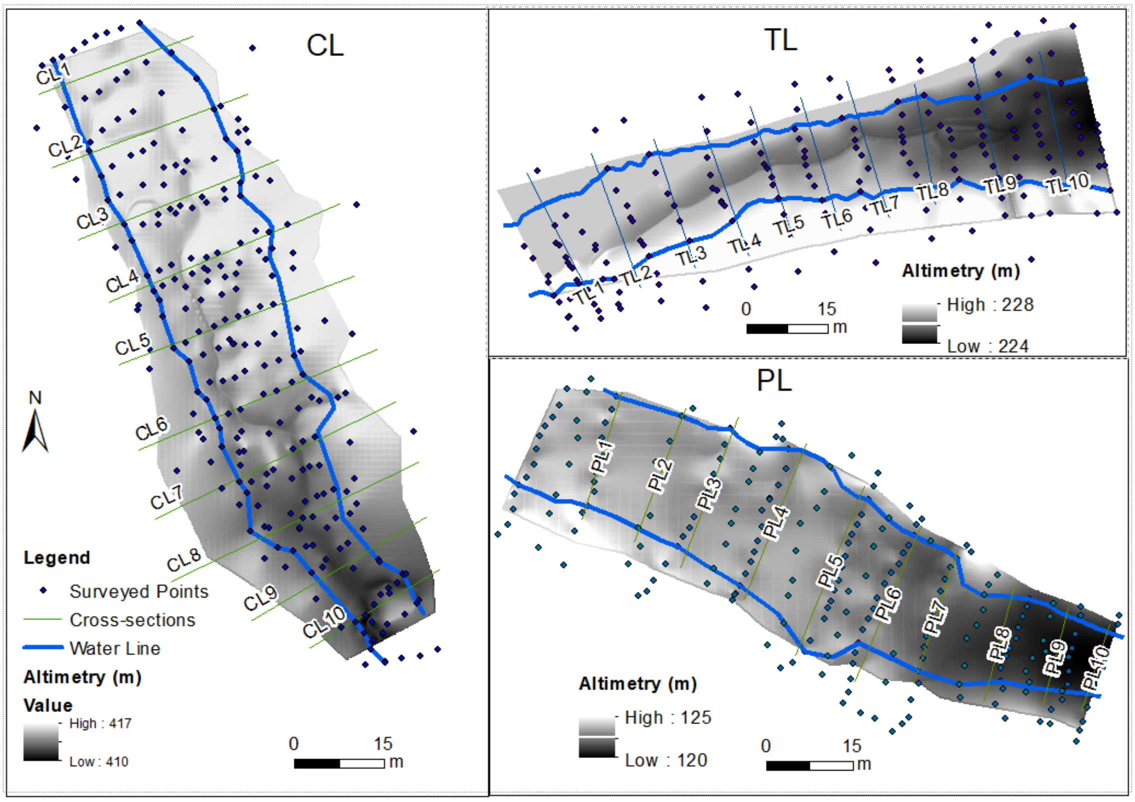

Figure 3-3 – DEM data, field surveyed points, and cross-sections in the CL, TL, and PL reaches.

Appendix B shows the measurement of the geomorphological parameters for each cross-section, and Figure 3-4 shows the descriptive statistics of the measured parameters. It is worth noticing that the bankfull width (W) in the reaches differs depending on the cross-section. Tsakiris et al. (2014) reported that large sediments and rocky outcrops in rivers might strongly affect water flow conditions, generating or modifying turbulence zones, sediment transport ratio, channel geometry, and grain size. In the study reaches, during high-flow periods, the CL reach featured higher D values, likely because the lateral constriction of the canyon walls allows the rapid increase of water levels during floods. However, it is worth noticing that the contribution area of the basin in the CL reach is smaller than that of the TL and PL reaches.

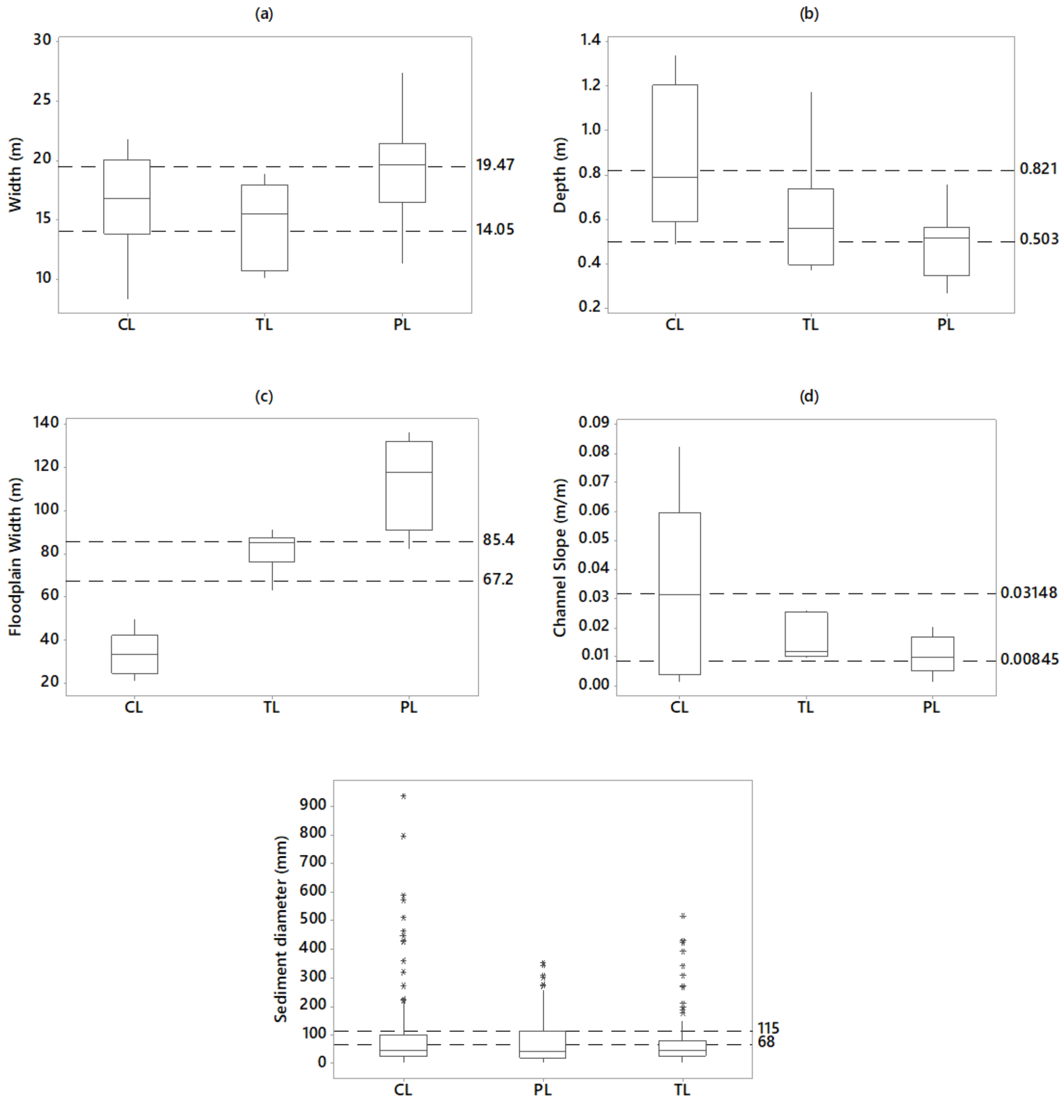

Figure 3-4 – Descriptive statistics of the measured parameters in CL, TL, and PL reaches: (a) Width; (b) Depth; (c) Floodplain Width; (d) Channel Slope, and (e) Sediment diameter. Dashed lines represent the decision limits of ANOVA considering α=0.05.

3.3.2 Geomorphic Features

Geomorphic features were identified in CL, TL, and PL reaches. We performed an ANOVA test (Figure 3-4), plotting the decision limits considering α=0.05. The results showed a significant difference between CL and PL for the floodplain width and channel slope. There is not enough statistical evidence to affirm the difference in treatment among the data for river width and depth.

We also compared means ($\bar{x}$), standard deviations (s), variances (s^2), and coefficient of variation (CV) between reaches (Appendix C). The results showed larger W values in PL and CL reaches, respectively, while TL features the smallest W. The same pattern is observed with the values of s, and s^2, revealing that TL reach is much more confined. Larger W values are expected downstream because more discharge is observed due to the increase in the contribution area, the reduction of the channel slope when the channel enters in the alluvial fan, and a consequent spread of the river channel, reaching wider areas. Such a situation is observed in the PL. However, the TL reach still presents a significant lateral constriction and water flow that remains a more regular pattern than the other two reaches. During low flow periods, it is not possible to observe the canyon walls constricting the river flow. However, during high flow periods, the river width will be similar to the floodplain width for the CL reach. Thus, at certain high flow conditions, W and FW become equal inside the canyon.

The results indicate a reduction in D values from upstream to downstream. This is counterintuitive, as D would generally become finer in the downstream direction. However, D depends on interactions between river and floodplain, mobility and bed material, geomorphic units, and fluvial patterns (Paixão and Kobiyama., 2019). Thus, such conditions observed in the three reaches may be related to the geomorphic units present in each reach and related to the river spread in the PL reach, allowing D to become smaller than the confined zone CL. Tsakiris et al. (2014) commented that large sediments might facilitate changes in the river channel characteristics. Because of the lateral constriction and the observation of large sediments changing the river channel, it is possible to verify large D in CL reach compared with PL reach. The FW values increase from upstream to downstream, as expected in a regular river basin. It is also worth highlighting that a canyon confines the river width during floods, and that over a certain threshold, higher discharges will be accommodated with higher D rather than increased FW.

The CL reach features a higher S than TL and PL. The results also show that the *s*, s^2, and CV in CL reach is higher than in other reaches, indicating a significant variation in this parameter along the entire reach. The slope is definitely the most critical parameter for characterizing mountain rivers, affecting hydraulic processes of discharge, sediment transport, geomorphic units, and alterations in flow regime (Wohl, 2010). In relation to sediment diameter, the descriptive statistics show that there are no differences between mean values in the three reaches. However, CL presents maximum sediment size as an outlier than TL and PL reach. It indicates that a substantial part of the grain size distribution is similar in the three reaches.

Sklar and Dietrich (1998) stated that mountain rivers englobe transitions between bedrock and gravel or between gravel and sand. Such shifts occur in all reaches. Nonetheless, the combined analysis of statistical parameters indicates that CL reach presents more expressive changes in S than other reaches, implying more transitions and complex interactions among hydraulic processes, sediment transport, and geomorphic units.

3.3.3 Cluster Analysis

The previous analysis of values of $\bar{x}$, *s*, $s^{2,}$ and CV are not effective in explaining the entire array of reach features. Thus, a cluster analysis was performed to identify similar patterns among the cross-sections. Figure *3-5* shows the dendrogram for the cluster analysis, and Table *3-1* shows the final partition of the clusters within-cluster sum of squares to infer the differences among the reaches.

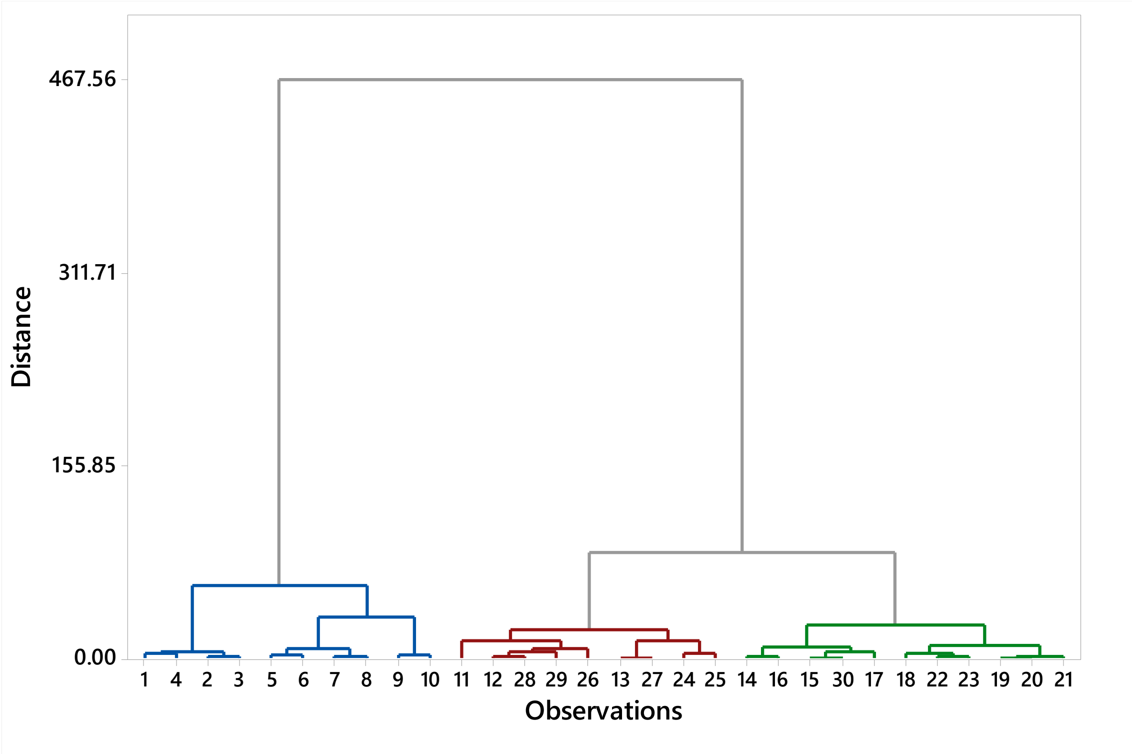

Figure 3-5 – Dendrogram of 30 cross-sections in the reaches. Observations: 1-10, 11-20, and 21-30 are related to the CL, TL, and PL reaches, respectively.

Table 3-1 – Final Partition of the Cluster Analysis.

	Cluster	Number of Observations	Within cluster sum of squares	Average distance from centroid	Maximum distance from centroid
Ward's Method	#1	10	1123.13	9.08628	17.0897
	#2	9	407.90	5.92982	12.3400
	#3	11	263.11	4.67426	7.0341

Clusters formed by Ward's Method showed three well-separated groups at the final partition, presenting 10, 9, and 11 observations in each set, respectively. It is possible to observe that only the former cluster belongs to the CL reach, even though the number of observations is similar to the number of cross-sections in each reach. Table *3-1* also indicates that the former cluster that compounds the CL reach also presents the larger values of the within-cluster sum of squares, the average distance from the centroid, and maximum distance from the centroid. This reinforces the hypothesis that CL is significantly different than TL and PL reaches.

The other two clusters are composed of a mixture of the cross-sections from TL and PL reaches. This indicates that TL and PL reach present some similarities between them in comparison to CL reach. Such conditions may also show that CL reach offers special geomorphic features and shapes that make them unique. It also indicates that the canyon influence on geomorphological parameters may reduce from upstream to downstream. However, defining precisely the transition zone is not a simple task. We highlight that most cross-sections present mountain rivers characteristics such as large slope, entrenched channels, gravel bedload sediments, and geomorphic units described by Paixão and Kobiyama (2019).

A significant concern about the cluster analysis calculated by considering the measured cross-sections is the aptitude of such measurements to correlate adjacent cross-sections because they are close to each other, which may bias the results. However, this condition is inherent to such an analysis on a reach scale. Less measurements would simply result in a lower accuracy of the results.

3.3.4 Geomorphic Units

Aiming to improve the geomorphological characterization of a canyon river, we analyzed the geomorphic units presented in each reach. We conducted a supervised automated procedure to classify the geomorphic units by using the GUT. The results show a consistent difference among the reaches in terms of geomorphic units (Figure 3-6). Although all reaches present the same type of geomorphic units (banks, pools, glide-runs, bars, and transitions), the distribution differs considerably among reaches.

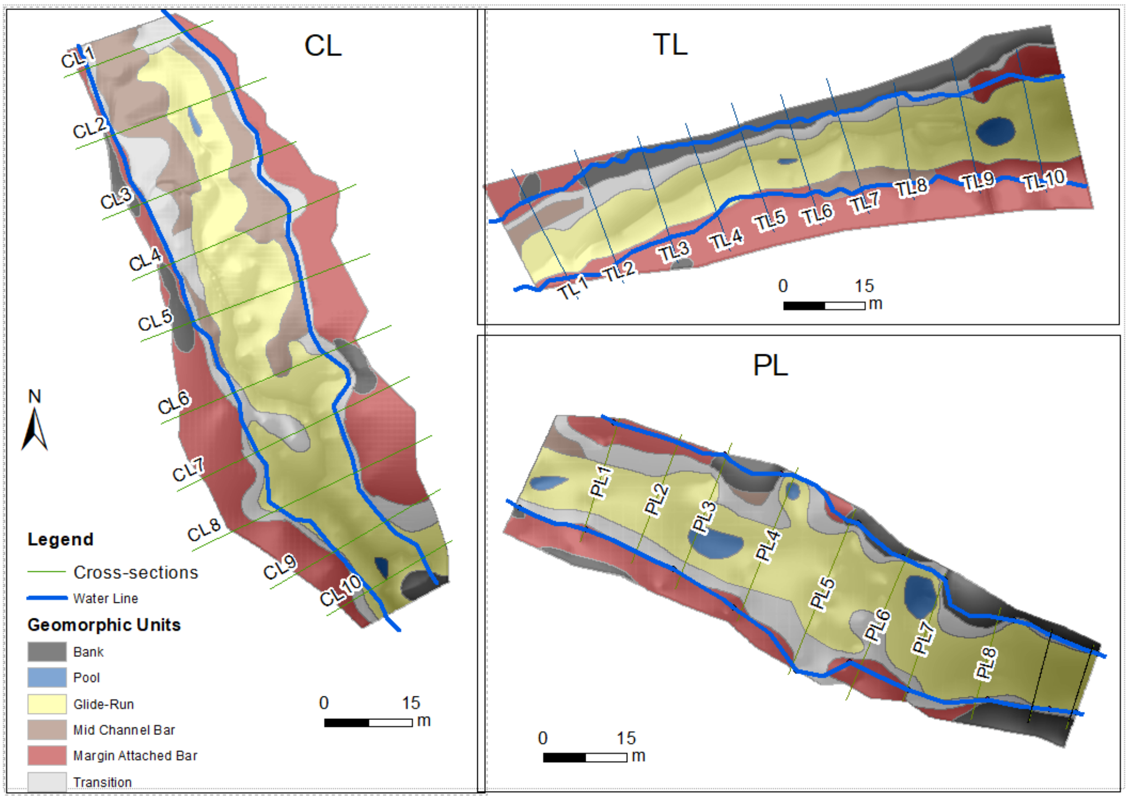

Figure 3-6 – Geomorphic units in CL, TL, and PL reaches

In CL reach, there are more bars than in TL, and PL reaches. Furthermore, the CL reach presents larger mid-channel bars in comparison with the other reaches. The short distance between the canyon walls and the river channel may explain this condition. Because the CL is confined within the canyon, it features a straight geometry. However, due to the sediment supply by the canyon walls, the current condition of the channel geomorphology is heterogeneous. The canyon walls feed sediments to the river by several rockfalls triggered by the natural process of contraction/expansion caused by the variation in temperature during the daytime. As the sediment source is remarkably close to the river, the sediments fall directly into the river, creating a bedrock channel with a heterogeneous assemblage of geomorphic units' distribution. Buffington and Montgomery (2013) mentioned these characteristics for steep headwaters rivers.

Results suggest that sediment supply is an essential characteristic of canyon's influence on river morphology. This condition improves the heterogeneity observed in the GUT and topographical results. The thalweg lines are more complex in CL than TL and PL reach. Thus, the TL reach presents a straighter longitudinal geometry than CL and PL reach in some way. Glide-runs were the main geomorphic unit in the TL reach, being laterally controlled by bars and banks. Two small pools are also present in the reach, especially at its end. The main difference from TL to the other reaches is that TL is supplied by sediments predominantly from upstream and from small tributaries.

Furthermore, the lateral supply of sediments occurs by bank and margin attached bar erosion or when a landslide or debris flow occurs around the reach. TL presents limited lateral sediment supply, contrary to CL, where sediments are supplied almost constantly due to rockfalls that occur independently of the water dynamics. Thus, the new geomorphic units in TL reach depend basically on sediment transport caused by the water dynamics. On the other hand, in CL reach, it depends both on water dynamics and rockfalls.

PL reach features a heterogeneous channel morphology, where glide-run is the most prominent geomorphic unit as observed in CL and TL reaches. However, some transitions to bars, mid-channel bars, and pools are heterogeneity distributed along the reach. It is important to note that PL reach is located in the alluvial fan area. According to Vasconcellos et al. (2021), the alluvial fans are prominent cone-shaped depositional forms. The alluvial fans have arisen from the distribution of sediments through erosional processes.

Furthermore, the alluvial fan characteristics include a lower slope, and wider channel width. Such lateral spreading of the river channel was observed in the mean values of *W* and *FW* (see Appendix C). In this way, the spread of the river channel and the depositional sediments induced heterogeneity in the PL reach, explaining such a "disorder" in geomorphic units.

Thus, the disorder in geomorphic units occurs by different processes in CL and PL reaches. Such disorder indicates a relevant difference in river behavior. While CL present sediment supply from the canyon walls and the water flow, the PL disorder represent the complex sediment deposition in the alluvial fans due to water flow.

3.3.5 Grain Size Distribution

Canyon rivers surveys are very challenging in terms of logistics and safety issues. In the CL reach, the increase in temperature in the first hours of sunlight causes the contraction/expansion on the rocks that compound the canyon walls, triggering several rockfalls in a large sort of sediment size. Such conditions associated with a long trail in a mountain environment to arrive in the CL reach reflects in a limited period of the daytime in which is safe to conduct field survey in the reach.

The reaches have been also compared in terms of grain size (Figure 3-7).

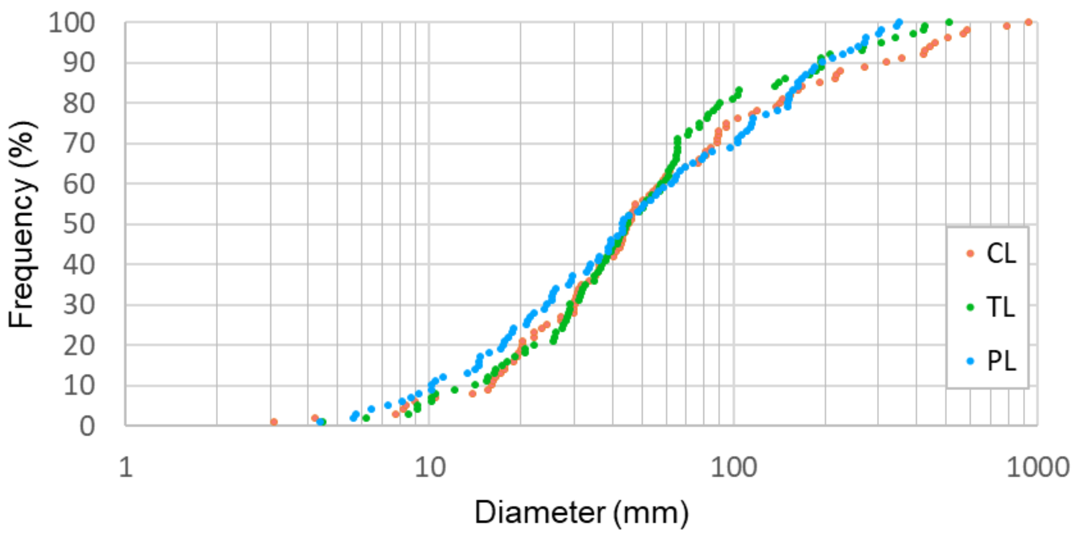

Figure 3-7 – Grain size distribution characteristics for the CL, TL, and PL reaches.

The maximum sediment size decreases from upstream to downstream. The CL reach features larger sediments than TL and PL. Although upstream reaches are expected to present larger sediments than downstream reaches, the reaches are very close to each other, and the natural downstream fining is not enough to explain this difference. Blom et al. (2016) reported that the sediment dynamics in mountain rivers, especially in canyon rivers, are overly complex and needed to be discussed and assessed.

Table 3-2 shows the typical values related to the diameter's characteristics. Three grain-size-distribution curves presented similar sediment size and medium diameter, d_{50}. However, at approximately d_{62}, the curves diverge. This may indicate that sediments up to d_{62} are frequently transported by the river, being this diameter related to the competence of the river, i.e., the maximum sediment diameter transported in normal conditions or regular floods. Coarser fractions on CL reach are likely due to sediments being recruited from the canyon rocky walls, and the grain size reveals that it is likely a semi-alluvial reach.

In the offset zone, the TL curve crosses the PL curves around d_{80}. Such a situation may be related to the input of sediments from hillslopes close to the TL reach. The TL region is considerably active in terms of landslides and debris flows occurrences, delivering sediments to the transition between canyon and floodplain in a large sort of sediment size. Harishidayat et al. (2018) commented that canyons are a kind of conduit of sediments, and Vasconcellos et al. (2021) commented that alluvial fans are the deposition zone of such sediments. Thus, the CL reach is the complex result of a legacy of sediment transport events with supply from upstream reaches and the walls of the canyons. Since deposited in the reach, some sediments can only be transported during high-magnitude/low-recurrence events. Such a condition allows the reach to present a large sort of sediment size, including large sediments.

Table 3-2 – Typical diameters for the CL, TL, and PL reaches

Typical diameters (mm)	CL	TL	PL
d_{16}	19	18	15
d_{50}	45	45	43
d_{62}	60	61	65
d_{83}	164	105	157
d_{90}	320	196	197
d_{100}	936	515	351

In a fine-sediments zone, the three reaches present a similar sediment size distribution. Fine sediments supply all reaches from upstream the canyon in the plateau area and from the entire basin. However, it is essential to state that the pebble-count procedure does not well sample fine sediments. Thus, small sediments are observed in all reaches, although the method does not measure them. The GUT results can infer some qualitative analysis, i.e., by the geomorphic units' characteristics in each reach. For example, bar units are present in all reaches, and they are composed of a large sort of sediments, including fine sediments. Similarly, small pools are present in the three reaches as in many mountain rivers (Paixão and Kobiyama, 2019).

3.3.6 Conceptual model with geomorphological characterization

Results suggest that canyon, transition, and floodplain landscapes differ in many ways as revealed by the field-based analysis. They feature different W, D, FW, S, grain size distribution, and geomorphic units' distribution. Sissakian and Jabbar (2009) and Venditti et al. (2014) reported that bedrock erosion in rivers determines the size, format, and relief of mountains. The field data suggest that the influence of bedrock erosion in the canyon weakens from upstream to downstream.

The grain size distribution curves for the reaches suggest that they present similar distribution. However, the canyon landscape offers a larger maximum sediment size than transition and floodplain. The field survey results also indicate that the canyon landscape shows a more complex river structure, such as the thalweg lines formed by a kind of "mess" of geomorphic units compared to the transition landscape. The floodplain landscape also presents a complex structure, but for different reasons, especially because of the alluvial fan characteristics reported by Vasconcellos et al. (2021) and those as mentioned above discussing.

Based on all considerations above, we propose a conceptual model for canyon rivers in Southern Brazil (Figure 3-8). The conceptual model highlights the three different reaches regarding their cross-section view, reaches' characteristics, geomorphic units, and grain size distribution.

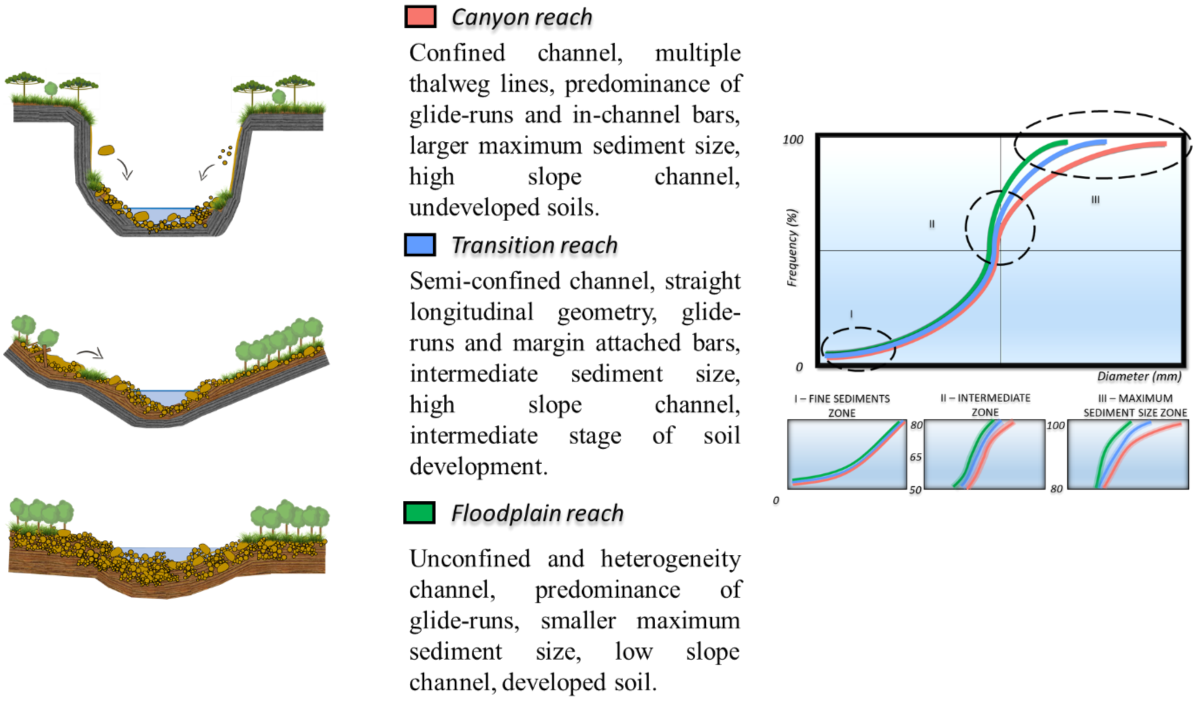

Figure 3-8 – Conceptual model of canyon rivers considering the cross-section view, channel pattern, geomorphic units, and grain size distribution.

The canyon reach is the reach confined by the canyon walls, being laterally constricted and acting as a conduit of sediments. Because of the river's proximity to the canyon walls, a wide range of sediment sizes are supplied directly onto the river channel. Such a condition creates a complex channel geometry with multiple thalwegs. The maximum sediment size is found in this reach. Large sediments trap fine sediments supplied from upstream the canyon creating bars, transported and deposited sediments create glide-runs and small pools. Because of the lateral constriction of canyon walls, the water level can increase faster in the canyon reach, facilitating the sediment transport of large sediments. Large sediments can be transported during large floods from this reach, as the water depth is increasing faster that other reaches due to the lateral confinement due to the rocky walls.

The transition reach is semi-confined, being laterally constricted not by the canyons' walls but steep hillslopes. Its primary source of sediments is different from that of the canyon reach. The sediments are transported by river and laterally supplied from landslides and debris flows. This lateral contribution is vital for the TL reach. Because it is the majority transportation zone, the channel geometry is straight, and glide-runs and margin-attached bars are predominant in a semi-confined space.

The floodplain reach is not laterally confined, featuring actually the characteristics of an alluvial fan. This reach receives sediments from upstream and suffers from remobilization of bed material during floods. Because of its low channel slope, the reach tends to deposit sediments, creating an alluvial fan in its deposition area. Such conditions allow the establishment of a complex system of geomorphic units caused by the spread of sediments in the alluvial fan area. The maximum grain size in the floodplain reach is smaller than in the canyon and transition reaches, while fine and intermediate sediments are similar. It means that the river frequently transports fine and intermediate sediments and that the general feature of sediment transport is similar along the main channel in the basin.

The river classifications commonly use parameters for supporting decision-makers of river management, and some of them are strongly related to mountain rivers. For example, channel patterns classifications (Lane, 1957; Leopold and Wolman, 1957; Schumm, 1977; Church, 2002, 2006; Brierley and Fryirs, 2005) use geometric plan view, entrenchment ratio, channel gradient, sediment size, sediment load, riparian vegetation, roughness, sinuosity, width, and depth for characterizing rivers. By analyzing these parameters and considering that channels present patterns in their extension, we developed the current conceptual model of a canyon river in Southern Brazil.

The model can support decision-makers of river management to delimit better conservational areas such as National Parks that aim to preserve the canyon environment. In the specific case of the Aparados da Serra region, which presents the largest canyon chain in South America, a better delimitation is particularly important to improve efforts on conservation. As Hardiman and Burgin (2010) reported, tourism in canyon areas has been increasing during the last decades, and therefore it is essential to improve efforts on conservation.

3.4 Conclusions

Canyon rivers are a particular case of rivers under the direct influence of canyon environments on sediment supply processes, sediment transport, grain size distribution, and geomorphic patterns. In other words, when sediments have been supplied directly from the canyon walls, or sediment transport occurs due to canyon landscape and landform influence, it represents a canyon river.

The present study showed that collecting data with field survey and remote sensing and identifying geomorphic units are useful for characterizing and classifying canyon rivers. Geomorphological characteristics such as *W*, *D*, *FW*, and *S* support the hypothesis that canyon, transition, and floodplain present different behaviors in terms of river morphometry. It implies a weakened influence of canyon on river characteristics from upstream (close to the gorge) to downstream (toward the floodplain). Furthermore, our analysis showed that CL reach has special conditions on morphometric parameters and geomorphic units. TL and PL present some similarities and differences among them.

Glide-runs are the most prominent geomorphic unit, despite banks, bars, pools, and transitions are present in the three reaches. The literature frequently reports these geomorphic units as those present in mountain rivers. Due to its position, the CL reach receives a large apport of sediment from canyon walls, facilitating middle-channel and margin attached bars and making the thalweg lines more complex. The TL reach presents a straight thalweg line and an important lateral constriction. The PL reach presents typical characteristics of alluvial fans.

A significant fraction of sediment size is frequently transported, according to the grain size distribution. In contrast, large sediments (larger than d_{80}) keep immobile or, at least, need fractioning for transporting or depositing somewhere. Alternatively, these sediments may be transported during debris flow events or discharges with a considerable return period. The field data also indicates that the valley shape can affect the sediment transport since the entrenchment caused by the canyon walls influences the water level, and consequently, the hydraulic conditions for incipient motion conditions.

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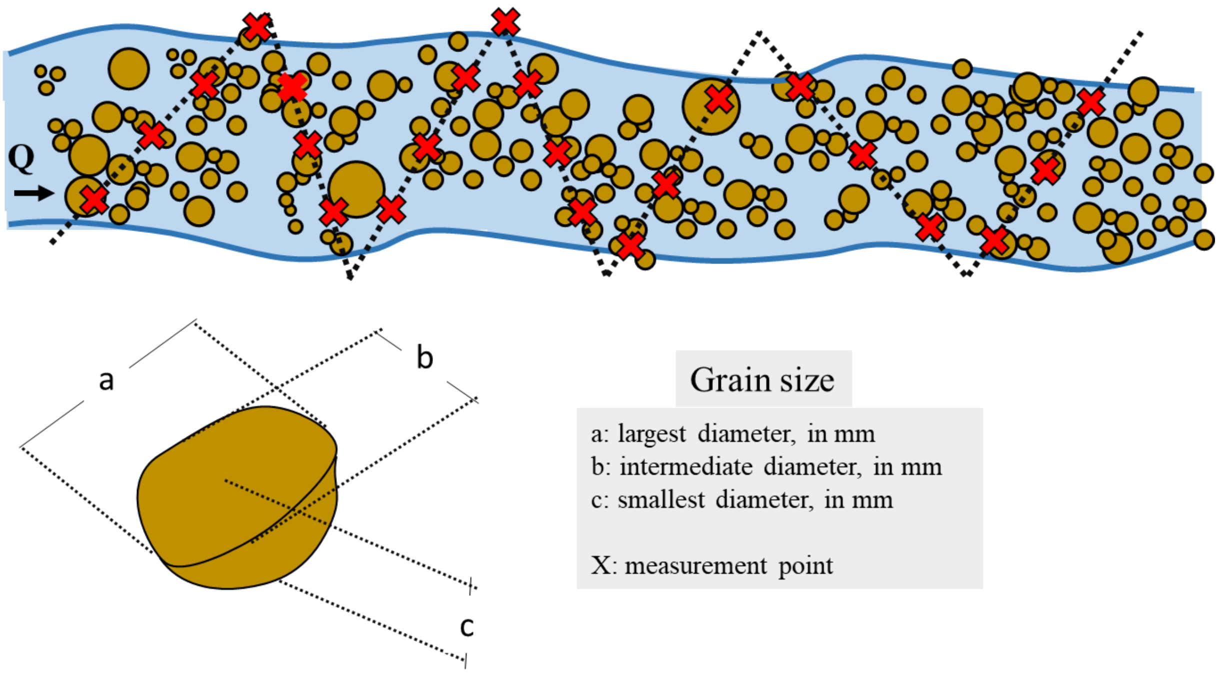
Appendix A

Performed sediment grain size measurements and analysis

The sediment size was surveyed using the zig-zag pebble-count procedure described by Bevenger and King (1995). It consists in covering the reach area walking in "zig-zag" from one margin to another collecting the clasts. They were collected, measured, and computed each 1 m, following the measurement description of Bunte and Abt (2001). In total, 100 clasts per reach have been sampled to perform the sediment size analysis. Despite some research papers present some critics regarding the extent of sediment size, surveying canyon rivers is a big challenge. Thus, it is considered an important advance this number of sampled clasts.



Appendix B

Results of the measurement of the geomorphological parameters for each cross-section

Cross-section	*W*	*D*	*FW*	*S*
CL_1	17.84	0.49	25	0.0031
CL_2	21.85	0.59	24	0.0042
CL_3	21.75	0.69	26	0.0062
CL_4	19.50	0.59	21	0.0013
CL_5	17.16	0.73	32	0.0235
CL_6	16.46	1.04	35	0.0523
CL_7	16.18	1.18	38	0.0392
CL_8	14.88	1.34	40	0.0825
CL_9	8.29	1.28	49	0.0595
CL_{10}	10.78	0.85	50	0.0595
TL_1	10.88	0.39	63	0.0099
TL_2	18.88	1.18	71	0.0103
TL_3	17.32	0.92	78	0.0096
TL_4	10.29	0.40	89	0.0260
TL_5	10.08	0.50	82	0.0219
TL_6	11.67	0.53	87	0.0254
TL_7	14.48	0.60	84	0.0106
TL_8	16.49	0.61	91	0.0120
TL_9	17.75	0.68	86	0.0256
TL_{10}	18.56	0.37	86	0.0116
PL_1	19.95	0.54	135	0.0063
PL_2	20.07	0.55	131	0.0065
PL_3	19.29	0.44	128	0.0077
PL_4	24.24	0.27	136	0.0120
PL_5	27.45	0.36	120	0.0016
PL_6	20.52	0.50	115	0.0163
PL_7	17.69	0.32	106	0.0016
PL_8	17.46	0.76	93	0.0203
PL_9	13.73	0.62	85	0.0180
PL_{10}	11.30	0.53	82	0.0144

Obs.: CL_N is the N-th cross-section along with the CL reach; TL_N is the N-th cross-section along the TL reach; PL_N is the N-th cross-section along the PL reach; W is the river width (m); D is the river depth (m); FW is the floodplain width (m); S is the channel slope (m/m); N is the upstream to downstream order.

Appendix C

Descriptive statistics of measured parameters on the three reaches.

	CL				TL				PL			
	$\bar{x}$	s^2	s	CV (%)	$\bar{x}$	s^2	s	CV (%)	$\bar{x}$	s^2	s	CV (%)
W	16.47	18.92	4.35	26.4	14.64	12.92	3.60	24.6	19.17	21.57	4.64	24.2
D	0.88	0.10	0.31	35.3	0.62	0.07	0.26	41.6	0.49	0.02	0.15	30.0
FW	34.00	105.78	10.28	30.2	81.70	76.46	8.74	10.7	113.10	423.21	20.57	18.2
S	0.0331	0.0009	0.0294	88.9	0.0163	0.0001	0.0074	45.3	0.0105	0.0000	0.0067	63.9

CHAPTER 4

4. Flow resistance in a canyon river: a case study of the Boi River in Southern Brazil

This chapter is based on the following manuscript to be submitted to Journal of Hydrology after the doctoral defense, entitled "Flow resistance in canyon river: a case study of the Boi River in Southern Brazil".

Abstract

We conducted several field surveys to measure velocity and channel geometry in 15 cross-sections distributed along three reaches in the Boi River, a canyon river located in Southern Brazil. The resulting data were used to compute the flow resistance. A downstream hydraulic geometry analysis indicates that the exponent describing the velocity increases with the discharge and that these values were between 0.3043 and 0.3507. The findings are coherent with other mountain river datasets, despite the Boi River present distinct geomorphic units, especially glide-runs, while other available datasets are characterized with step-pool channels. Regression analysis of the combined field dataset indicated that dimensionless unit discharge is an important independent variable to explain variations in velocity and flow resistance. We also verified that the use of Rickenmann's Equation, can be helpful to estimate velocity in canyon rivers. Our findings include: i) canyon landscape presents higher friction factors than floodplain landscape: and ii) canyon and transition landscapes are similar in terms of flow resistance during high-flow conditions, while floodplain present remarkably differences.

Keywords: canyon river, friction factor, flow resistance

4.1 Introduction

Compared to lowland rivers, hydraulics in steep mountain rivers is poorly understood (Aberle and Smart, 2003). Furthermore, mountain and alluvial rivers differ in characteristics such as slope, roughness, spatial and temporal variability of bed material, channel geometry, entrenchment ratio, and sediment supply (Wohl, 2010; Vasconcellos et al., 2021). In addition, Buffington and Montgomery (2013) commented that surveying mountain rivers is logistically a big challenge, more dangerous and expensive than that of large lowland rivers. When considering mountain rivers carving canyons, such a challenge becomes much more significant. Therefore, studies on canyon rivers are still scarce, even though canyons are present all over the world.

Recent advances in knowledge related to canyon rivers include the valley formation (Lamb et al., 2006; Cook et al., 2009; Zhang et al., 2020), fluvial processes (Nester et al., 2007; Waele et al., 2010; Venditti et al., 2014; Gasparini et al., 2014; Vasconcellos et al., 2021), sediment transport (Inbar and Schick, 1979; Webb et al., 1999; Topping et al., 1999; Nester et al., 2007; Zhang et al., 2020), and management (Kearsley et al., 1999; Harpmann et al., 1999; Mazzali et al., 2021). After an extensive search, we verified that, although some authors have studied river flow in canyons, there is no investigation on flow resistance of canyon rivers.

As Comiti et al. (2007) reported, studies involving flow resistance in a high-gradient channel have been done in the last decades. However, most of them were carried out using flume modeling (i.e., Rickenmann, 1991; Maxwell and Papanicolau, 2001; Aberle and Smart, 2003), and just a few with field survey (i.e., Lee and Ferguson, 2002; Comiti et al., 2007; Afzalimehr et al., 2011). Thus, a direct comparison of the flow resistance between high-gradient channels and canyon rivers relies on advancing the investigation of canyon rivers.

Our study explored factors influencing flow velocity and resistance in a canyon river to develop predictive equations for these hydraulic variables. We used field data of discharge, velocity, channel morphology from three reaches located in the canyon, transition, and floodplain landscapes along the Boi River, located in Southern Brazil. It is worth mentioning that the Boi River belongs to the most extensive canyon chain in South America. The field data were analyzed and compared to other mountain rivers datasets in order to verify whether predictive equations for mountain rivers are suitable for canyon rivers.

4.2 Resistance Equations

One of the main ways to analyze the flow resistance in open channels is the Darcy-Weisbach friction factor:

$$ff = 8gR_H S v^{-2} \tag{4.1}$$

where *ff* is the Darcy-Weisbach friction factor; *g* is the gravitational acceleration (m/s²); R_H is the hydraulic radius (m); *S* is the channel slope (m/m), and *v* is the flow velocity (m/s).

Several authors proposed resistance equations for mountain rivers (Egashira and Ashida, 1991; Rickenman, 1991; Bathurst, 2002; Aberle and Smart, 2003; Afzalimehr et al., 2011). However, most of them impose limitations either on the premises or on the study object. The former is commonly related to the assumption of rectangular cross-sections. The latter is the fact that many researches were conducted in step-pools channels. Thus, these kinds of equations are suitable just for the step-pool morphology.

Flow resistance of coarse-bed channels depends on flow velocity, channel slope, water depth, and grain size (Sui et al., 2010). Based on flume studies, Rickenmann (1991) developed equations to describe the flow resistance considering the hydraulic parameters above mentioned and two distinguished situations:

$$v = 1.3g^{0.20}S^{0.20}q^{0.60}{D_{90}}^{-0.40} \qquad 3\% < S < 40\% \tag{4.2}$$

$$v = 0.37g^{0.33}S^{0.20}Q^{0.34}{D_{90}}^{-0.35} \qquad S > 0.8\% \tag{4.3}$$

where q is the discharge per unit width (m^2/s); D_{90} is the 90th percentile of bed grain size distribution (m) used to represent roughness; and Q is discharge (m^3/s).

Rickenmann (1991) conducted experiments to measure the flow resistance of clay suspension with and without bedload transport for different channel slope conditions. Because of a large set of physical conditions in Rickenmann's experiments, we verified here the validity of his equations to predict the river flow in canyon rivers.

4.3 Methods

4.3.1 Study area

The study area is the Boi River basin (128 km^2), located at the border between the Rio Grande do Sul and Santa Catarina state, Southern Brazil (Figure 4-1). The region is characterized by the bluffs of the Serra Geral Formation, especially basaltic spills (Paixão et al., 2021). Such geological formation dates back to the Gondwana rupture and the South Atlantic formation, highlighting the area's geological heritage. Furthermore, similar geological formations are observed in Western Africa, especially in Namibia. Thus, it reinforces the environmental and geological relevances of the study area.

The hillslopes are steep, presenting significant altimetric variation with vigorous embedded valleys and canyons that open, forming alluvial fans. The basin altitude varies between 1012 and 85 m.a.s.l. The Itaimbezinho canyon inside the Boi River basin has a 5.8-km length and 500-m height. The regional climate types are Cfb and Cfa upstream and downstream of the canyon, respectively. The precipitation is well-distributed along the year with an annual mean of 1800 mm.

The Boi River basin belongs to the Aparados da Serra National Park (PNAS), one of Brazil's most important conservation areas and the most extensive canyon chain in South

America. The basin hosts a project for monitoring water with experimental facilities operating since 2017 in the PNAS area, where one meteorological and two fluviometric stations are measuring data every ten minutes.

We chose three reaches with approximately 50-m length to perform this study (Figure 4-1). The reaches' characteristics are described in detail by Paixão et al. (Submitted):

i) Canyon Landscape (CL): presents a typical canyon view, deeply incised on bedrock, located entirely inside the Itaimbezinho Canyon. The mean channel slope is 0.03 m/m;

ii) Transition Landscape (TL): a typical mountain environment, with an entrenched valley with steep hillslopes. The mean channel slope is 0.016 m/m;

iii) Floodplain Landscape (PL): a typical alluvial fan environment where the floods spread broadly. The mean channel slope is 0.010 m/m.

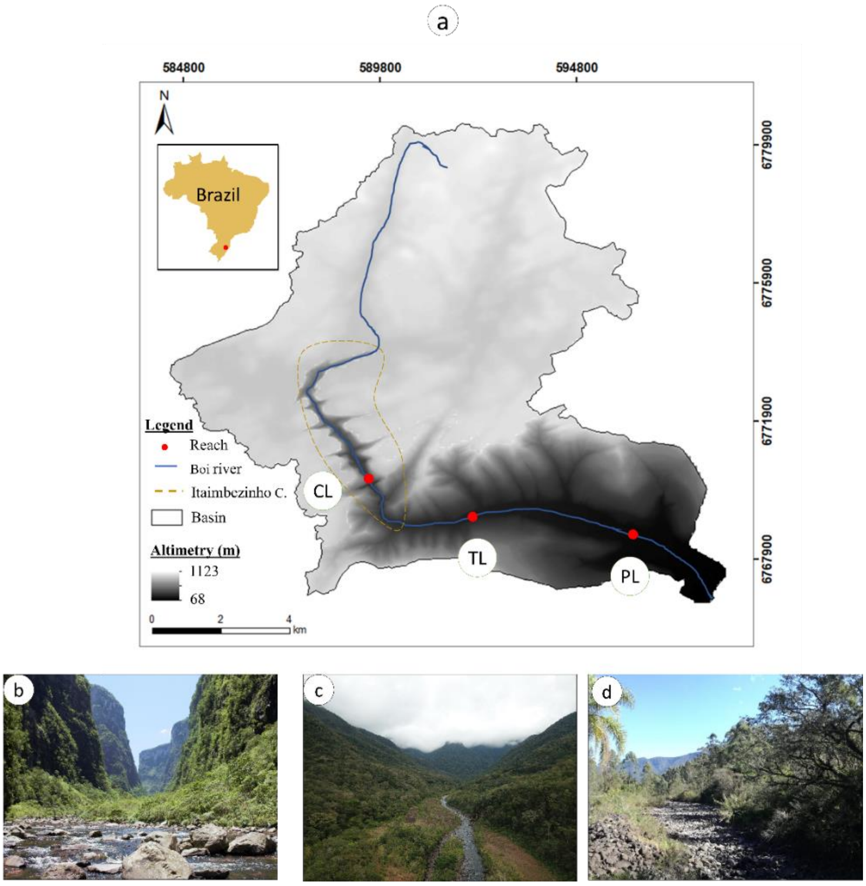


Figure 4-1 – Study area: a) Boi River basin; b) CL reach; c) TL reach; and d) PL reach (Source: Paixão et al., submitted)

4.3.2 Field Measurements and Analysis

In order to obtain digital elevation model data with 0.10 m resolution for the three study reaches, extensive topographic and bathymetric surveys were carried out in the Boi River basin using a total station and an RTK-GPS. These field surveys have been conducted since the beginning of the long-term monitoring project in the PNAS area. Furthermore, we conducted the field surveys during low-flow days due to a dangerous situation with high flow.

We constructed a rating curve by measuring discharges ranging from 0.2 to 36 m^3/s. Then, discharges higher than 36 m^3/s were estimated by the rating curve, which may cause inherent uncertainty to canyon rivers analysis. We verified the water level during several field surveys conducted in the Boi River during the project execution, correlating water level, discharge, and river flow velocity in the three study reaches.

We chose three reaches (CL, TL, and PL) to analyze the *ff* values in these reaches, in each of which five cross-sections were selected as representative ones for the corresponding landscape. According to Paixão et al. (Submitted) which applied the Geomorphic Units Tool (GUT) developed by Wheaton et al. (2015), the three reaches present an interaction of geomorphic units as glide-runs, mid and margin attached bars, pools, and banks. Besides, we used the previous data of grain size distribution obtained by Paixão et al. (Submitted). We also calculated the standard deviation of the grain size distribution (σ_g).

We calculated the downstream hydraulic parameters (Gleason et al., 2015) using the software HEC-RAS (USACE, 2010). The obtained data were the flow width, wetter area, hydraulic radius, and flow velocity. As we monitor the water level every ten minutes and the rating curve is available, we could establish a relation between flow discharge and water level for the three reaches. Thus, we performed steady-flow simulations for a considered discharge which was the peak discharge for each considered event. The HEC-RAS uses equations of mass conservation and momentum (Teng et al., 2017). As a monitoring-time interval in the field is

10 minutes, we considered a 10-minutes steady-flow simulation. The observed values of water level obtained by the two fluviometric stations were used for model calibration. Thus, when the discharge fits the water level, the model was considered calibrated. We adopted a Manning's roughness coefficient (n) varying between 0.06 and 0.08 to best describe the surveyed conditions, which is reasonable for the Boi River conditions.

Vasconcellos et al. (2021) utilized n=0.03 to alluvial rivers in the Mampituba River basin where the Boi River basin is located. Though this n value can be useful for alluvial fans, it may not represent the environmental conditions of the present study in a high steep channel. The use of simulations were crucial especially for high flow events (upper than 36 m^3/s), for which we had the discharge estimation and the water level observations. The use of steady-flow simulations is helpful in these cases because the main goal is to evaluate the downstream hydraulic geometry for the cross-sections at a given condition. The general characteristics of the three reaches are shown in Table 4-1.

Table 4-1 – Characteristics of three study reaches in the Boi River

Reach	***S* (m/m)**	**D_{16} (mm)**	**D_{50} (mm)**	**D_{84} (mm)**	**σ_g (-)**
CL	0.030	19	45	198	2.96
TL	0.016	18	45	137	2.75
PL	0.010	15	44	163	3.33

Besides the *ff* value, we calculated the Froude Number for each cross-section:

$$Fr = \frac{v}{\sqrt{g \cdot d}} = \frac{v}{\sqrt{g \cdot \frac{A}{w}}} = \frac{v}{\sqrt{g \cdot \frac{\left(Q/_{v}\right)}{w}}} \quad (4.4)$$

where Fr is the Froude Number; d is the flow depth (m); w is the river width (m); A is the wetted area (m^2); and v is the mean flow velocity (m/s).

River flow prediction plays an essential role in water resource management, such as planning projects, irrigation systems, hydroelectric power systems, and water supply systems (Adnan et al., 2017). As river flow in canyon rivers remains unclear in terms of their mechanisms, the use of predictive equations can be useful to preliminarily describe the flow in such areas. Thus, in order to verify if Rickenman's (1991) predictive equation is suitable for canyon rivers, we directly compared the observed velocities with those predicted with Rickenmann's Equation. In addition, we calculated the errors between predicted and observed velocities:

$$error\ (\%) = \frac{v_{obs} - v_{pr}}{v_{obs}} \cdot 100 \tag{4.5}$$

where v_{obs} is the observed flow velocity (m/s); and v_{pr} is the predicted flow velocity (m/s).

4.3.3 Combined Field Data for Mountain Rivers

We combined our data with five other datasets from mountain rivers to explore factors that influence mountain rivers' velocity and flow resistance. Here it is worth to mention that none of 5 datasets is related to canyon rivers but step-pool rivers in mountain environments. Lee and Ferguson (2002) studied the Pennine hills, England, over a range of low to intermediate discharges; MacFarlane and Wohl (2003) and Curran and Wohl (2003) studied the Cascade Range, Washington, USA; Wohl and Wilcox (2005) studied streams in New Zealand. Comiti et al. (2007) studied the Rio Cordon in Italy. These 5 studies were carried out in mountain streams with typical step-pools morphology. This analytic comparison was done to investigate if the Boi River presents similar behavior to step-pool streams concerning *ff*.

As this dataset of mountain rivers has a large range because of different channel geometry and hydraulic conditions, we evaluated the data in non-dimensional manner, similarly to Aberle and Smart (2003), Comiti et al. (2007), and Ferguson (2007):

$$v^* = \frac{v}{\sqrt{gD_c}} \tag{4.6}$$

$$q^* = \frac{q}{\sqrt{gD_c^3}} \tag{4.7}$$

where v^* is the non-dimensional velocity; v is the velocity in m/s; q^* is the unit non-dimensional discharge; and D_c is the roughness parameter which is usually considered approximately equal to D_{84}.

4.4 Results and Discussion

4.4.1 Hydraulics in the Boi River

Five representative cross-sections in each reach were selected to perform the downstream hydraulic geometry analysis (Figure 4-2).

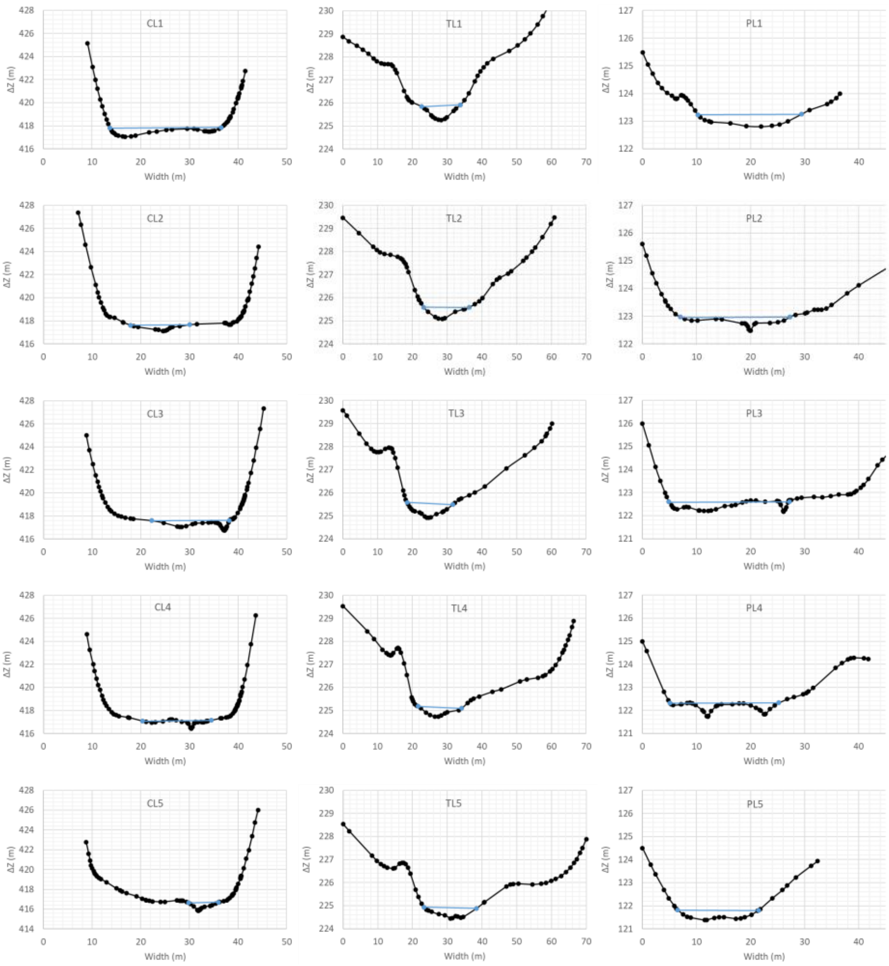


Figure 4-2 – Cross-sections considered in the present study.

The columns represent CL, TL, and PL reaches, respectively. Blueline represents the water level during the survey.

The mean values of *v* varied slightly among the CL, TL, and PL reaches, ranging from 0.66 $m.s^{-1}$ (CL_1, *Q*=2.05 $m^3.s^{-1}$) to 3.52 $m.s^{-1}$ (TL_5, *Q*=236 $m^3.s^{-1}$), meanwhile the mean values of *Q* were from 2.05 $m^3.s^{-1}$ to 275 $m^3.s^{-1}$.

Figure *4-3* shows that the velocity exponent *m* ranged from 0.3043 to 0.3507, and velocity coefficient *k* ranges from 0.5068 to 0.6212 where $v = kQ^m$. The depth exponent *f* ranges from 0.3260 to 0.4209, and the depth coefficient *c* ranges from 0.2747 to 0.5298 where $d = cQ^f$. The width exponent *b* ranges from 0.1607 to 0.3072, and the width coefficient *a* ranges from 9.1347 to 13.67 where $w = aQ^b$.

The analysis of the downstream hydraulic geometry (Figure *4-3*) indicated that *D* increases immediately with *Q* in CL than TL and PL, while *v* tends to increase similarly among the three reaches. Meanwhile, in TL and PL, depth increased more rapidly with discharge than velocity. Furthermore, velocity and depth increase more quickly than river width. The similar mean velocity and small depth in PL imply a large spread of the water flow in the terrain. The PL reach presents typical characteristics of an alluvial fan, as described by Vasconcellos et al. (2021). On the other hand, CL offers specific attributes of canyon rivers, as defined by Paixão et al. (Submitted). The TL reach presents *D* values more similar to PL for low-flow conditions and to CL for high-flow conditions, which characterizes a transitional manner between canyon and floodplain (alluvial fan) characteristics.

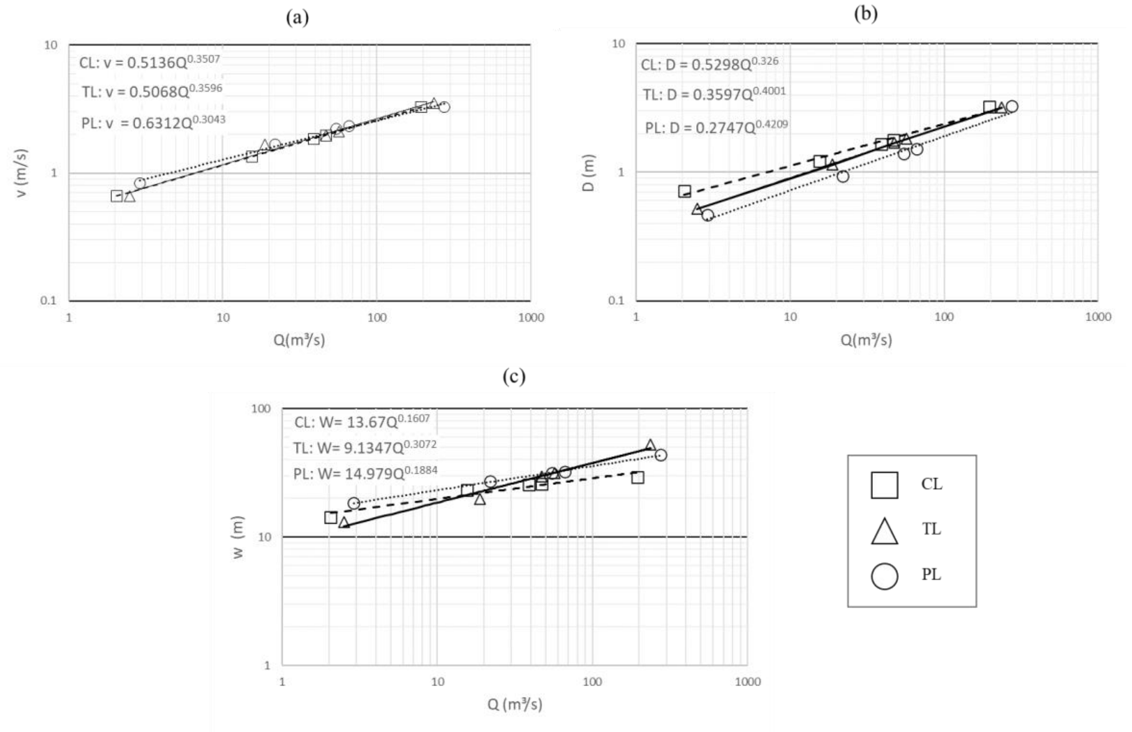


Figure 4-3 – Downstream hydraulic geometry for the study reaches in the Boi River: a) reach-averaged velocity (*v*) vs. discharge (*Q*); b) flow depth (*d*) vs. discharge (Q); and c) width (*w*) vs. discharge (Q).

Table 4-2 – Verification of the downstream hydraulic geometry for the CL, TL, and PL reaches and for the Boi River.

Reach	***b+f+m***	***a.c.k***
CL	0.8304	3.719
TL	1.0669	1.665
PL	0.9136	2.597
Boi River	0.9532	2.320

Table *4-2* indicates that the hydraulic geometry concept was not fully verified in the Boi River. It was expected that $b+f+m=1$ and $a.c.k=1$ to validate the hydraulic geometry (Gleason, 2015). However, for CL, PL, and TL, the findings show a dispersion of $b+f+m$ around 1. For the Boi River dataset, the result was the closest to 1. When analyzing the $a.c.k$, the results varied considerably. Studies involving hydraulic geometry usually consider the alluvial river (i.e., Allen et al., 1994; Grison and Kobiyama, 2011; Julien, 2015). Studies considering mountain rivers usually do not present the verification $b+f+m$ or $a.c.k$ (i.e., Lee and Ferguson, 2002; Comiti et al., 2007). Thus, there might be a theoretical limitation on the hydraulic geometry applications to mountain rivers. However, despite such limitations of $b+f+m$ and $a.c.k$, we demonstrate a substantial difference between CL, TL, and PL. It indicates that efforts on hydraulic geometry for mountain rivers should be made, and they are helpful to describe such environments.

The CL presented subcritical ($Fr < 1$) conditions for all discharges though field survey visual evidence clearly indicated that supercritical flow occurs locally. The TL shows similar behavior to CL reach. For PL, supercritical ($Fr > 1$) conditions were observed at two cross-sections during low-flow conditions and some semi-critical flow (Fr = 0.92 to 0.97) at the discharges of 22 and 66.2 $m^3.s^{-1}$. The general feature of the Boi River data is $Fr < 0.7$. The Fr values in PL differ statistically from those in the other two reaches. It can be noted that PL presents a large variation in Fr besides larger median values and dispersion (*Figure 4-4*).

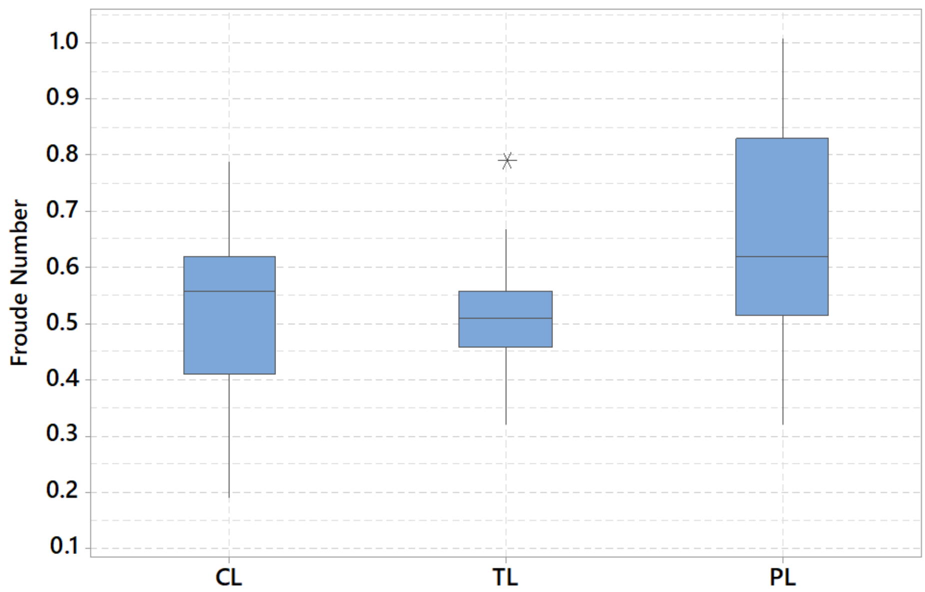


Figure 4-4 – Froude number for CL, TL, and PL reaches.

The Fr values for the Boi River dataset permits to obtain a general value of 0.7, although some visual observations indicate Fr>1 in some reaches. With Eq. (5), the Fr calculation was done considering the entire cross-section area. Thereby, some supercritical flow can be observed partially at certain places in the cross-section, while *Fr* indicates a subcritical flow. Paixão et al. (submitted) commented that the spread of the river channel and the depositional sediments induced heterogeneity in the PL reach and caused a kind of "mixture" in geomorphic units presented in the reach. Thus, many transitions in these geomorphic units may cause a significant variation in *Fr*.

4.4.2 Flow Resistance in the Boi River

The relation between *ff* and *Q* is shown in Figure 4-5 for each reach under distinct flow conditions.

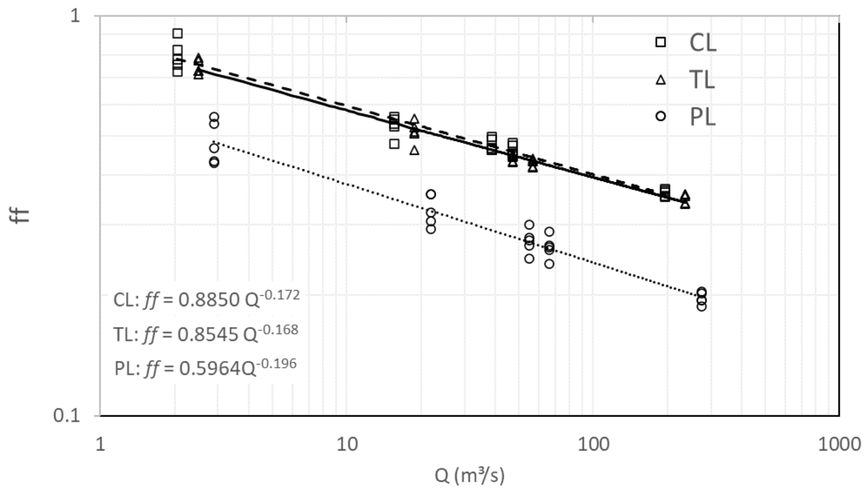


Figure 4-5 – Relation between Darcy-Weisbach friction factor (*ff*) and discharge (*Q*) in the Boi River reaches

The decrease of *ff* ranges between -0.168 and -0.196, indicating that the flow resistance decreases approximately with the fifth root of *Q*. The highest values of *ff* occur in low-flow periods as expected, and the CL reach presents higher flow resistance during the considered discharges in the present study. The CL reach presents the steepest gradient, the coarsest grain size distribution, the lowest average velocities, and the most significant channel roughness among the three reaches. The lowest mean velocities may be related to the mixture of geomorphic units that improve roughness to the channel and reduce its velocity despite the reach present the higher channel slope. The TL reach presents a flow resistance behavior similar to CL meanwhile PL reach differs considerably. The lowest *ff* values were measured and observed in PL. Even though lower discharges present lower *ff* values, the PL reach shows the lowest resistance for all considered discharge events.

Jarrett (1982) observed a reduction in the flow resistance due to reducing the channel slope along mountain rivers. Such a decrease was also reported by Comiti et al. (2007) and suggested by Eq. (4.1). In addition, according to Eq. (4.1), v increases more quickly than R_h. Thus, a *ff* reduction can be expected with an increase in Q.

We demonstrated that the flow resistance is considerably more significant for a reach inside a canyon than outside. Such a difference is probably related to the landform characterized by canyon rivers and grain size distribution on the canyon. When the river flow fills the canyon during the rainfall event, the hydraulic radius increases immediately in CL than in PL, elevating the flow resistance. In addition, the *ff* reduction with the increase in discharge is similar to the n decrease reported by Asano and Uchida (2016), where the influence of channel roughness is more significant for low discharges than high discharges.

In general, the calculation of flow resistance in steep channels is sensitive to measurement errors of channel geometry. By performing a detailed topographic and bathymetric survey (0.10 x 0.10 m of resolution), we attempted to reduce the Rh and d measurement errors. However, this kind of error can inevitably persist due to various factors like riverbed mobility. In addition, our data could be affected by several factors associated with the precision in velocity estimation: i) the use of a rating curve which may underestimate or overestimate data, and ii) the inherent errors in the methods used for measuring velocities in the Boi River.

4.4.3 *Effects of Unit Discharge on Velocity*

We examined the relationship between v^* and q^*, both of which are non-dimensionalized parameters with D_{84} as the roughness parameter D_c in Eq. (4.6) and (4.7). The regression considering the entire dataset (N = 75, R^2 = 0.881) for the Boi River was:

$$v^* = 0.60 \cdot q^{*0.45} \qquad (4.8)$$

We also analyzed the CL, TL, and PL reaches individually (Figure 4-6). The data shows that coefficients for the three reaches do not vary in an extensive range. The values of coefficient *m* and *k* vary from 0.50 to 0.72 and 0.39 to 0.52, respectively. As mentioned above, due to the lateral constriction of canyon walls, the hydraulic radius increases immediately in CL than in PL during the rainfall event, elevating the flow resistance. It implies an increase in q^* when D_c is almost constant along the entire Boi River. Similar to datasets in step-pool rivers (Aberle and Smart, 2003; Comiti et al., 2007), we also found that q^* is an important variable for describing velocity in canyon rivers.

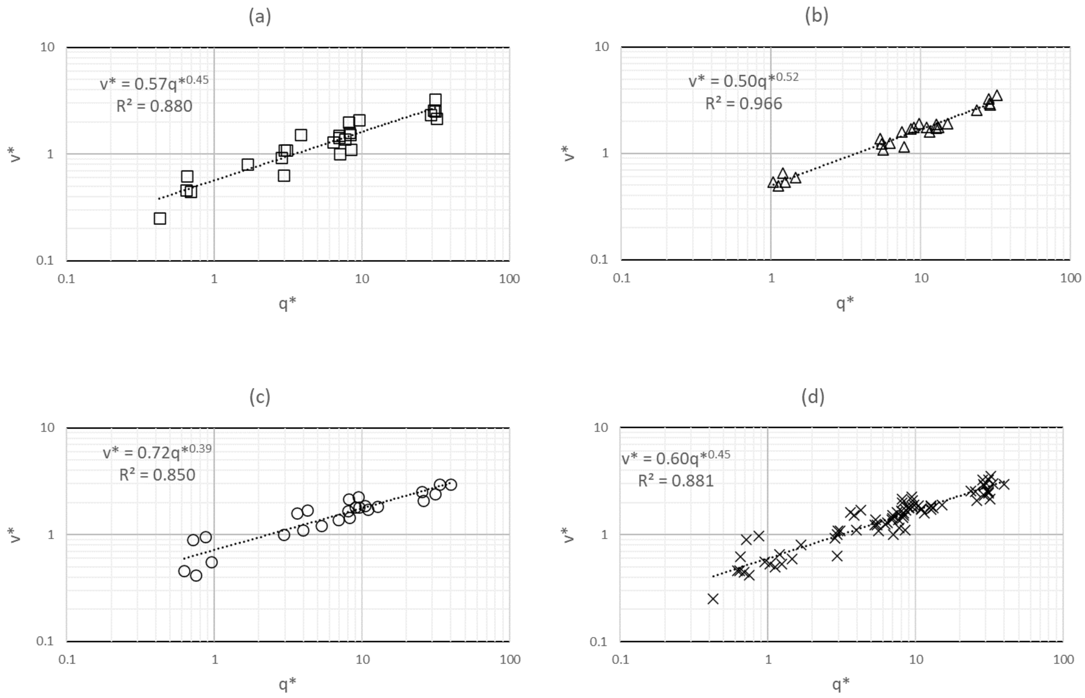


Figure 4-6 – Dimensionless relationship between velocity and discharge: (a) CL; (b) TL; (c) PL; and (d) Boi River.

Table *4-3* demonstrates the results for the reaches and the entire Boi River, beyond comparison to other datasets. The results indicate that q^* was an important independent variable for explaining v^* for a large dataset. Comiti et al. (2007) found similar results, including q^* and S as important independent variables.

Table 4-3 – Parameters of v* and q* for the Boi river and other datasets

Dataset	**N**	**Fr**	$v^* = mq^{*k}$		
			m	***k***	R^2
Boi river	75	0.19 – 1.01	0.60	0.45	0.881
CL reach	25	0.19 – 0.79	0.57	0.45	0.880
TL reach	25	0.32 – 0.79	0.50	0.52	0.966
PL reach	25	0.32 – 1.01	0.72	0.39	0.850
Comiti et al. (2007)	44	0.15 – 0.96	0.97	0.62	0.781
Wohl and Wilcox (2005)	24	0.12 – 0.68	0.71	0.44	0.799
Curran and Wohl (2003)	20	0.05 – 0.39	0.93	0.81	0.935
MacFarlane and Wohl (2003)	17	0.08 – 0.29	0.66	0.55	0.833
Lee and Ferguson (2002)	70	0.01 – 0.52	0.76	0.68	0.801

4.4.4 Friction Factor Relationships

We also examined the relationship between *ff* with q^* (Figure 4-7). In addition, we compared the relationships with literature for mountain rivers. The relation between *ff* and q^* discharge follows the Equation obtained by linear regression on the log-transformed data (N = 75; R^2 = 0.516):

$$ff = 0.621 \cdot q^{*-0.22} \tag{4.9}$$

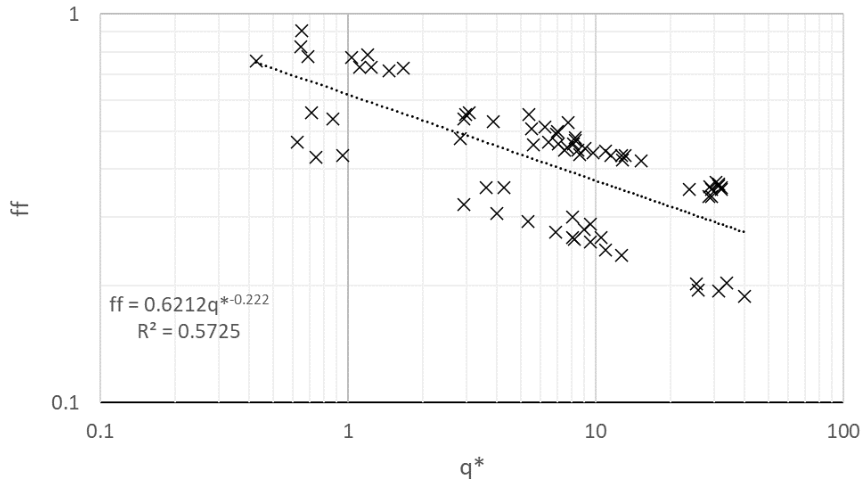


Figure 4-7 – Relationship between friction factor *ff* and dimensionless unit discharge *q**

We obtained an overall negative relationship between *ff* and *q** as observed in the literature. The comparison with five other datasets which studied mountain rivers shows distinct characteristics among the individual datasets (Table 4-4). Curran and Wohl (2003) and Comiti et al. (2007) recorded higher resistance factors at comparable dimensionless unit discharge, while Wohl and Wilcox (2005) recorded the lower resistance factors. Curran and Wohl (2003) developed their studies on a channel with strong contribution to large woods, what may induce resistance to flow. Comiti et al. (2007) conducted their studies in a step-pool channel with largest channel slope among the considered dataset. According to Eq. (4.1), the channel slope directly influences on the flow resistance. On the other hand, Wohl and Wilcox (2005) presented the lowest *ff* values. It occurs probably because their studies were conducted in the lowest channel slope among the datasets. The Boi River assumed a consistent flow resistance in comparison with the other dataset for mountain rivers for compared value of *q**, however, it presents the lower decrease of the friction factor with discharge.

Table 4-4 – Parameters of the best-fit equations ff for the datasets

Dataset	Location	Morphology	Basin area (km^2)	Channel slope ($m.m^{-1}$)	D_{50} (mm)	N	$ff = Aq^{*B}$		
							A	*B*	R^2
Boi River	Boi River, Brazil	Glide-run	128	0.01 to 0.03	45	75	0.621	-0.22	0.516
Comiti et al. (2007)	Rio Cordon, Italy	Step-pool	5	0.136	110	44	1.90	-0.47	0.215
Lee and Ferguson (2002)	Pennine Hills, England	Step-pool	ND	0.027 to 0.097	170 to 360	70	0.79	-1.26	0.458
MacFarlane and Wohl (2003)	Cascade Range, USA	Step-pool	< 5.9	0.061 to 0.14	104 to 181	17	1.38	-0.79	0.52
Curran and Wohl (2003)	Cascade Range, USA	Step-pool	< 10	0.06 to 0.18	30 to 103	20	2.82	-1.04	0.676
Wohl and Wilcox (2005)	Porter and Kowai River, New Zealand	Step-pool	< 30	0.003 to 0.20	38 to 450	24	0.45	-0.77	0.465

4.4.5 Velocity Prediction

We compared predicted and observed velocities (*Figure 4-8*) using Rickenmann's equations (Eq. 4.2 and 4.3) obtained with flume studies, not with natural river channels. For the Boi River dataset, the predicted velocities for CL, TL, and PL reaches have an average error of 21.1%. Considering the CL, TL, and PL reaches individually, the average errors were 28.3%, 17.6%, and 17.4%, respectively. The maximum error (84%) occurred in CL_1 under a discharge of 195 $m^3.s^{-1}$, while the minimum error (0.05%) occurred in PL_5 under a discharge of 22 $m^3.s^{-1}$.

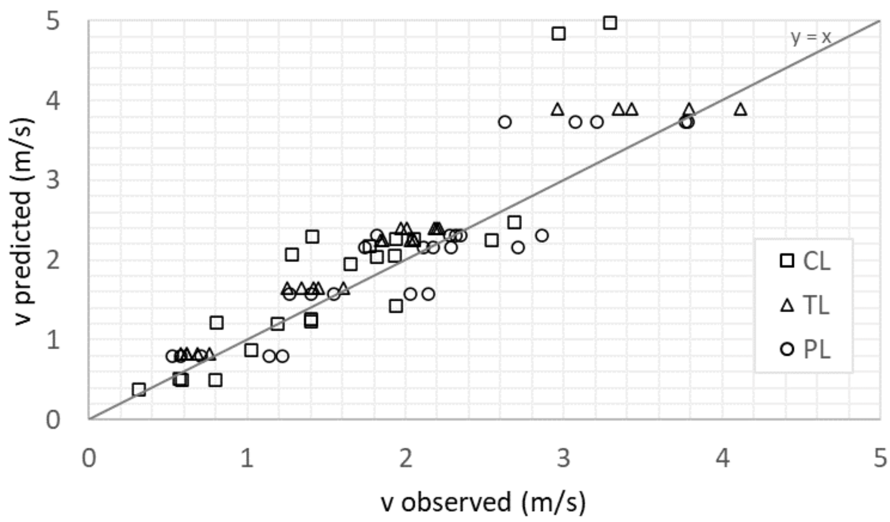


Figure 4-8 – Predicted vs. observed velocities in the Boi River.

As a general trend, Rickenmann's equations overestimate velocities for the Boi River. Comiti et al. (2007) reported underestimation for flow velocities over 1 m/s. However, we observed an apparent overestimation for velocities above 3 $m.s^{-1}$. The remarkable difference occurred in CL reach, in which the observed velocity was 2.77 $m.s^{-1}$, and the predicted velocity was 5.11 $m.s^{-1}$, an error of 84.6%. For velocities up to 3 $m.s^{-1}$, Rickenmann's Equation presents a dispersion around the y=x line, which indicates a very good fitting. The flow velocity of 3 $m.s^{-1}$ implies discharges above 195 $m^3.s^{-1}$ in the Boi River. Here it is worth mentioning that the field survey to obtain the topographical data was conducted just under a discharge of 2 to 3 m^3/s during a low-flow period. It, therefore, allows saying that Rickenmann's Equation is helpful to describe flow velocities in canyon rivers in Southern Brazil, especially in the cases that flow velocity monitoring is not feasible.

4.5 Final Remarks

Canyon rivers surveys are logistically a big challenge and more dangerous than those in large lowland rivers, especially during high flow conditions. As observed in other studies, estimations of various parameters are susceptible to field-measurement errors. Many researchers (e.g., Bathurst, 2002; Comiti et al., 2007) discussed that steep mountain rivers present problems to apply resistance laws, primarily because of the quality of input parameters which are difficult to obtain. However, the downstream hydraulic geometry approach combined with the field obtained data might provide greater insight into the role of flow resistance in canyon rivers, supporting estimation of the river flow conditions.

Comiti et al. (2007) commented that the scarcity of field data limits the ability to derive statistically sound at-a-station analysis. Thus, the field measurements permitted us to broaden the findings related to flow resistance in the Boi River which is located inside the most extensive canyon chain in South America.

By considering the limitations of resistance laws establishment, we decided to use a simple, efficient, and straightforward resistance-law, i.e., the Darcy-Weisbach Equation. Despite the inherent uncertainties, the findings include i) canyon landscape presents higher friction factors than floodplain landscape; and ii) canyon and transition landscapes are similar in terms of flow resistance with higher flow condition, meanwhile, floodplain present remarkably different friction factors. Probably, geomorphic units and D_{max} exert an essential role in determining flow resistance. Its verification should be done in future research.

Supplementary measurements of canyon rivers will be required to expand the findings on this type of river that presents particular importance due to its geological heritage and environmental characteristics. Furthermore, new intermediate reaches between the canyon and floodplain should be investigated. Such efforts will improve the knowledge of the hydrogeomorphological aspects of canyon rivers.

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CHAPTER 5

5. Conclusions and Recommendations

5.1 Conclusions

The present doctoral dissertation aimed to perform a hydrogeomorphological classification of a canyon river in Southern Brazil. As canyon rivers are a particular case of mountain rivers, evaluating relevant parameters for characterizing this kind of river was realized to discuss state of the art. Furthermore, it was discussed the Brazilian scenario on research in mountain rivers and its challenges.

Parameters such as channel slope, the relation between width and depth, entrenchment ratio, discharge, sediment load, and grain size distribution are crucial to characterize mountain rivers. These parameters are recommended as a minimum requirement for describing mountain rivers. Field surveys and observations are mandatory for the complete characterization, although they require financial expenditure and time. Therefore, it emphasizes the importance of field hydrometry in mountain rivers. Furthermore, improving field-survey-based investigations is a demand for the scientific community in the world as well as in Brazil.

Studies considering canyon rivers, a particular case of mountain rivers, are even more scarce than mountain rivers. Here, canyon rivers are concluded to be those rivers under the direct influence of canyon environments on sediment supply processes, sediment transport, grain size distribution, geomorphic patterns, and hydraulics influence. Thus, the definition of a canyon river exceeds the place where sediment has been supplied directly from the canyon walls.

The findings also include that canyon, transition, and floodplain landscapes present different behaviors in terms of river morphometry. Furthermore, the influence of canyon in river characteristics weakens from upstream (close to the gorge) to downstream (toward the floodplain). In addition, thalweg lines in canyon landscapes are more complex than transition and floodplain reach. Finally, glide-runs are the most prominent geomorphic units along the canyon river, although other geomorphic units can be present. A significant fraction of sediment size is frequently transported concerning sediment transport, while sediments larger than d_{80} keep immobile.

The analysis of the friction factors provided an important insight into the role of flow resistance in canyon rivers. Canyon landscapes present higher resistance to flow than floodplain landscapes. The differences between canyon and floodplain are remarkable, evidencing hydrogeomorphological differences among these reaches in the same river in a short space. Such differences are may related to geomorphic units and the grain size, despite the channel slope. Dimensionless unit discharge is an important predictor

5.2 Recommendations

Though studies of mountain rivers are more dangerous and expensive than those in lowland rivers, field surveys are needed to improve the scientific knowledge of mountain rivers. In the case of canyon rivers, such a challenge is even more significant. For these reasons, hydrometry, topography, and topobathymetry in situ are crucial. Thus, efforts to conduct field surveys in mountain and canyon rivers are strongly recommended.

The field surveys may support the advance on canyon rivers' subjects and also be helpful to the river classification. Therefore, the recommendation is to use hierarchical classifications on different scales (river, segment, reach, channel units, etc.) for classifying mountain rivers.

The classifications and the investigation of canyon rivers may help decision-makers to delimit better conservational areas such as National Parks to preserve the canyon environments. In the specific case of the Aparados da Serra National Park, a better delimitation is essential to improve efforts on conservation in the most extensive canyon chain in South America and raise tourism sustainably.

Thus, it is recommended to the Aparados da Serra National Park and to the community around the study area:

- Improve efforts on monitoring canyon rivers in the Park's area by installing equipment such as linimetric scale, water level sensors, and meteorological stations;
- Report occurrences of flash floods and debris flow in the National Park area;
- Promote environmental education on hydrology to improve safety in tourism in the region, especially in trails inside the canyons;
- Revise the delimitation of the Park's area considering canyon rivers as the rivers under the influence of the canyon as described in this document;
- Avoid promoting land occupation in the canyon river basin to prevent extreme hydrological events in mountain areas.

For future investigations on canyon rivers, some topics should be investigated, as follows:

- Assess the sediment incipient motion in canyon rivers;
- Evaluate the spatio-temporal variability of geomorphic units;
- Evaluate the soil thickness in the three reaches using geophysics methods;
- Assess the influence of the margin slope on river characteristics and landforms;
- Characterize the vegetation in different portions of the canyon river and evaluate their differences;
- Assess the conditions of occurrence of extreme hydrological events, such as debris flood and debris flow by remobilization of bed material;
- Analyze the relation between resistance flow and Reynolds number in the three reaches;
- Investigate the flow resistance in other canyon rivers according to the geological formation;

- Verify the validity of the hydraulic geometry in canyons;
- Develop predictive field-based flow velocities equations for canyon rivers in Southern Brazil.