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Differences in the occurrence of debris flows in tropical and temperate environments: field observations and geomorphologic characteristics in Serra do Mar (Brazil) and British Columbia (Canada)

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Abstract

Debris flows are among the most destructive types of mass movements throughout the world and are not restricted to certain climate zones or geological environments. In opposite corners of the American continent, Canada and Brazil have experienced several historic debris flows. As part of a one-year international exchange program, the lead author compared morphological evidence related to debris flows and the morphometry of watersheds at sites in Canada and Brazil, with the ultimate goal of improving the understanding of debris flows in Brazil. Field surveys carried out in both areas in 2019 and 2020 permitted observation of the debris-flow signatures, as well as the physical aspects of the surrounding areas and morphometric mapping of watersheds. Both areas exhibit similar typical features of debris flows, and the morphometric results indicate differences that may influence the recurrence of events at the sites in Canada as compared to Brazil due to their higher values for the parameters area > 25° (A25), relief ratio (Rr), and Melton ratio (Mr) at the Canadian sites; however, this dataset is limited. Compared to results in the literature from around the world, values of morphometric parameters at Brazilian sites are within the ranges observed in other tropical climates.

KEYWORDS: debris flow; mass movement; field survey; DEM; GIS; morphometry.

INTRODUCTION

Among landslide types, debris flows stand out due to their high flow velocities, impact forces, and travel distances. Debris flows are defined by Hungr *et al.* (2014) as very rapid to extremely rapid surging flows of saturated debris in a steep channel, which cause damage and casualties when they occur in occupied areas (Eisbacher and Clague 1984, VanDine 1996, Jakob and Hungr 2005). Prerequisites for triggering debris flows include an abundant source of sediments, steep slopes, sparse vegetation, and an excess of water, which is typically provided by rainfall events or snowmelt (Johnson 1970, Costa 1984, Iverson *et al.* 1997, Wilford *et al.* 2004, Jakob 2005). Debris flows are not restricted to specific zones; these events occur in different parts of the world, such as Asia, North America, Europe, and South America (Jackson *et al.* 1987, Marchi *et al.* 2002, Carrara *et al.* 2008, Gabet and Bookter 2008, Gomes *et al.* 2008, Chen and Yu 2011, Dias *et al.* 2016, 2021b, 2022; Picanço *et al.* 2016, Sujatha and Sridhar 2017, Sujatha 2020, Coe *et al.* 2021). Critical volumes of precipitation are the most common factor reported as the main trigger of debris flows. Recent catastrophic occurrences in South America reported precipitation thresholds of at least 130 mm, highlighting the events in Venezuela in 1999, with 911 mm in 48 h (García-Martínez and López 2005), Colombia in 2018, with 130 mm in 3 h (García-Delgado *et al.* 2019), and in Brazil in 2011, with 250 mm in 48 h (Avelar *et al.* 2013, Coelho-Netto *et al.* 2013, Lima 2017).

Over the last 60 years, the recorded number of debris flows and shallow landslides has become more frequent in Brazil, including in the Serra do Mar Mountains and on the south and southeast coasts. Remarkable disastrous events occurred in Caraguatatuba (1967), Rio de Janeiro Mountain range and Serra da Prata (2011), and Itaoca (2014), causing economic and social losses and stressing the need for mitigation measures, as well as a susceptibility assessment (Ploey and Cruz 1979, JICA 1991, Coelho-Netto *et al.* 2013, Gomes and Vieira 2016, Facuri and Picanço 2020, Lima *et al.* 2020, Dias *et al.* 2021a). These events caused social damage (more than 3,000 deaths) and economic losses (at least $3 billion (USD)) (World Bank 2014, Kanji *et al.* 2017). Nevertheless, debris flow research and practice in the country still lags behind other affected areas worldwide, with few local papers published about this issue (Kanji *et al.* 2008, Gomes *et al.* 2008, 2013, Jackson 2011, Dias *et al.* 2016, Campos and Galindo 2016, Roverato 2016, Lopes *et al.* 2016, Facuri and Picanço 2020, Cabral *et al.* 2021). In comparison, debris flows are one of the most common and well-documented landslide processes in some parts

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of Canada, particularly in the province of British Columbia on the west coast (Thurber Consultants LTD. 1983, VanDine 1985, Slaymaker 1990, Scally *et al.* 2001). According to Strouth and McDougall (2021), debris flows represented more than 50% of the fatal landslides in British Columbia between 1950 and 2019; however, fatalities caused by the process are considered rare (one death per year in the last decade) despite the population growth, which reflects the development of mitigation measures and the number of detailed studies about the process.

The morphometric evaluation of watersheds affected by debris flows has been used as an important tool for understanding features that may contribute to debris flow occurrence. Many studies evaluate debris flow occurrences in North America and Europe, including studies carried out by Scally *et al.* (2001, 2010), Jakob (1996), and Slaymaker (1990) in different areas of British Columbia, Canada; Cenderelli and Steven Kite (1998), Gabet and Bookter (2008), Kovanen and Slaymaker (2008), Welsh and Davies (2011), and Wilford *et al.* (2004) in the USA; Portilla *et al.* (2010) in the Pyrenees Mountains, Spain; Dotseva and Gerdjikov (2020) on Stara Platina Mountain and Nikolova *et al.* (2020) in the Eastern Rhodopes, Bulgaria; and Ilinca (2021) in the Carpathians, Romania. Most of these studies evaluate the debris flow process under a specific climatic condition, in this case, a temperate environment, which has very specific characteristics in comparison to a tropical environment. Detailed studies about debris flows in tropical environments are still lacking, especially studies using morphometric parameters and those regarding Brazilian occurrences.

Although far apart, we hypothesize that areas located in different hemispheres may present similarities and specificities related to the occurrence of debris flows, which can help improve the understanding of the process in places like Brazil, where detailed studies are historically lacking. To this end, this study aimed to compare debris flow field observations and morphometric characteristics of example watersheds in Canada with recently affected areas in Brazil, highlight their main differences and similarities, and compare them to results from different parts of the world reported in the literature. The parameters area (A), drainage density (Dd), area > 25° (A25), relief ratio (Rr), length (L), basin relief (Br), and Melton ratio (Mr) were selected due to their use in the literature and practice for the evaluation of debris flow areas in the northern hemisphere, in a temperate environment (VanDine 1985, Jakob 1996, Scally *et al.* 2001, Wilford *et al.* 2004, Kovanen and Slaymaker 2008, Portilla *et al.* 2010, Welsh and Davies 2011, Zubrycky *et al.* 2021, Ilinca 2021) and the southern hemisphere, in a tropical environment (Augusto Filho 1993, Vieira *et al.* 1997, Kanji and Gramani 2001, Chen and Yu 2011, Dias *et al.* 2016, Gomes 2016, Picanço *et al.* 2016, Cerri *et al.* 2018, Lima *et al.* 2020).

REGIONAL SETTINGS OF THE STUDY AREAS

Two of the study areas, Lillooet and Mount Currie, are located in North America, in the province of British Columbia, near the west coast of Canada (Figs. 1A and 1B). The other case study areas, Itaoca and Serra da Prata, are located in South America, near the southeast coast of Brazil (Figs. 1C and 1D). Although located in different environments, both sets of areas have geologic, geomorphic, and climatic conditions that contribute to the occurrence of debris flows.

Geomorphology, geology, soil, and vegetation

Lillooet and Mount Currie are part of the Cordilleran Mountain System. They are situated near the boundary between the Coast Mountains and Interior Plateau. They have a predominance of steep mountains and U-shaped valleys with mass wasting on hillslopes at high elevations, and they range from 100 to > 2,000 meters above sea level (Church and Ryder 2010). The geology in Lillooet includes sedimentary rocks, which are mostly sandstone, conglomerate, argillite, and siltstone from the Cretaceous period (Church and Ryder 2010, Cui *et al.* 2017). The Mount Currie geology is mostly igneous rocks, particularly Cretaceous granite (Bovis and Evans 1995, Church and Ryder 2010). The soil type in both areas is major spodosols and inceptisols (Clayton *et al.* 1977, Soil Classification Working Group 1998), covered by montane forest and subalpine forest (Natural Resources Canada 2021).

Itaoca and Serra da Prata are located in Serra do Mar, a mountain system that extends for approximately 1,500 km along the south and southeast coasts of Brazil (Almeida and Carneiro 1998, Vieira and Gramani 2015). These study areas have predominantly V-shaped valleys, hills, steep mountains, and elevations ranging from 200 to 1,100 meters above sea level (Almeida 1964, MINEROPAR 2006). The geology in Itaoca and Serra da Prata includes igneous and metamorphic rocks from the Archean-Proterozoic, particularly granite and gneiss (Perrotta *et al.* 2005, ITCG 2006, Faleiros *et al.* 2012). The soil cover is ultisols and oxisols (Ross 2002, ITCG 2008, Picanço *et al.* 2016, Rossi 2017) and the vegetation is the Atlantic rainforest (IFSP 2009, ITCG 2009).

Climate

The climate varies among all the study areas despite their proximities and geological and geomorphological contexts. In Canada, Lillooet is defined as a temperate/Mediterranean continental climate (Dsb) (Koppen 1936, Amani *et al.* 2019), with mean temperatures varying between -4 and 20°C in the winter (Dec. to Mar.) and summer (Jun. to Sep.) seasons, respectively. The average monthly rainfall distribution shows little variability in the amount of rain, which does not exceed 50 mm per month, and the average annual total is 316 mm (Fig. 2A). At Mount Currie (less than 100 km south of Lillooet), the climate is defined as a temperate/humid continental climate (Dfb) (Koppen 1936, Amani *et al.* 2019), with mean temperatures varying between -6°C in the winter (Dec. to Mar.) and 18°C in summer (Jun. to Sep.) seasons. Despite the relatively similar temperatures to those at Lillooet, the rainfall distribution throughout the year is distinct, with an average annual rainfall of 947 mm; the wet season occurs between October and March (autumn-winter) and the relatively dry season occurs between April and September (spring-summer) (Fig. 2B).

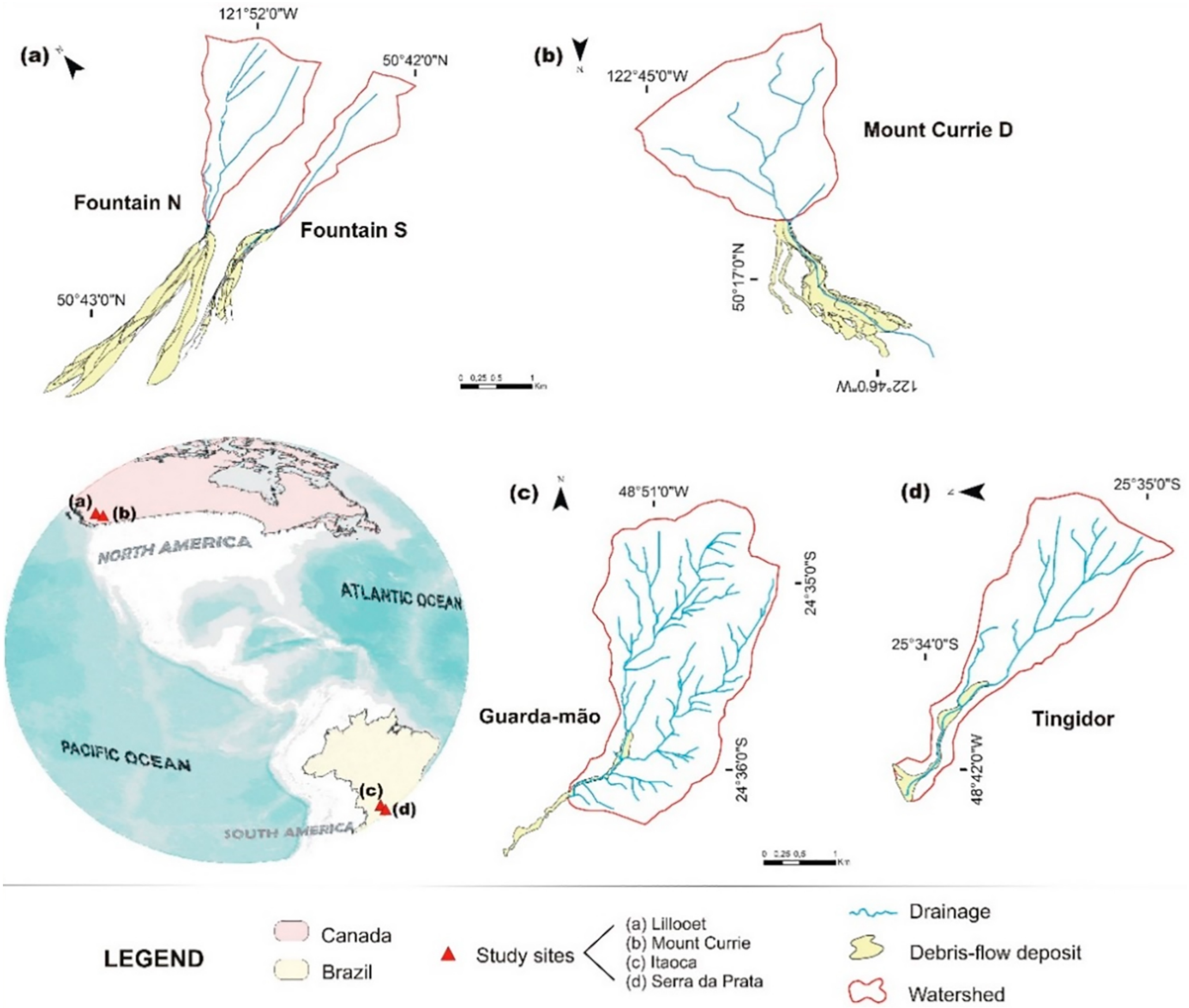


Figure 1. Location of the study areas in (A and B) Canada, (C and D) Brazil, and the respective watersheds.

The climate in Itaoca is defined as a humid subtropical climate (Cfa) (Koppen 1936), with the mean temperature varying between 17°C in the winter season (Jun. to Sep.) and 25°C in the summer season (Dec. to Mar.). The monthly multiannual rainfall distribution is high in the summer season and reaches 200 mm in January, which is only 115 mm less than the annual value in Lillooet. The average annual total rainfall in Itaoca is 1,345 mm, which is more than 4 times higher than that in Lillooet (Fig. 2C). In comparison, Serra da Prata is defined as having a Cfa climate at altitudes below 700 m and a temperate oceanic climate (Cfb) at altitudes above 700 m, with mean temperatures varying between -3°C in the winter season (Jun. to Sep.) and 22°C in the summer season (Dec. to Mar.) (Koppen 1936, Blum 2006, Blum *et al.* 2011). Monthly rainfall varies between 61 mm (Aug.) and 222 mm (Jan.), with an average annual total of 1,463 mm, according to 30 years of data from 1970 to 2000 (Fig. 2D).

Occurrence of debris flows

The study site near the town of Lillooet is on Fountain Ridge, east of town. Debris flows occur in two different watersheds, designated Fountain North (*FN*) (Fig. 3A) and Fountain South (*FS*). At least 13 events have been identified at these sites since 1948, the most recent of which occurred in 2018 (Zubrycky 2020, Zubrycky *et al.* 2021). The study site at Mount Currie is south of the town of Pemberton; this study focuses on a watershed designated Mount Currie D (*MD*) (Fig. 3B). At least 19 events have been identified at these sites since 1946 (Zubrycky *et al.* 2021).

In comparison, only one debris flow has been observed in Itaoca, in the Guarda-mão watershed (*GW*), in 2014 (Fig. 4A) (Brollo *et al.* 2015, Gramani and Martins 2016, Dias *et al.* 2022), and only one event has been observed at Serra da Prata in the Tingidor watershed (*TW*), in 2011 (Fig. 4B) (Picanço and Nunes 2013, Ferreira *et al.* 2016, Facuri and Picanço 2020). Both events mobilized a large volume of sediments, affecting infrastructure and causing human fatalities. According to Brollo *et al.* (2015), since 1997, Itaoca has been affected by at least 5 critical events, most of which were related to floods and flash floods, with the last one in 2014 being the only one involving debris flows and shallow landslides (Dias *et al.* 2022).

MATERIAL AND METHODS

Field surveys

The data used in this paper were obtained by field surveys conducted between 2019 and 2020. A total of five debris

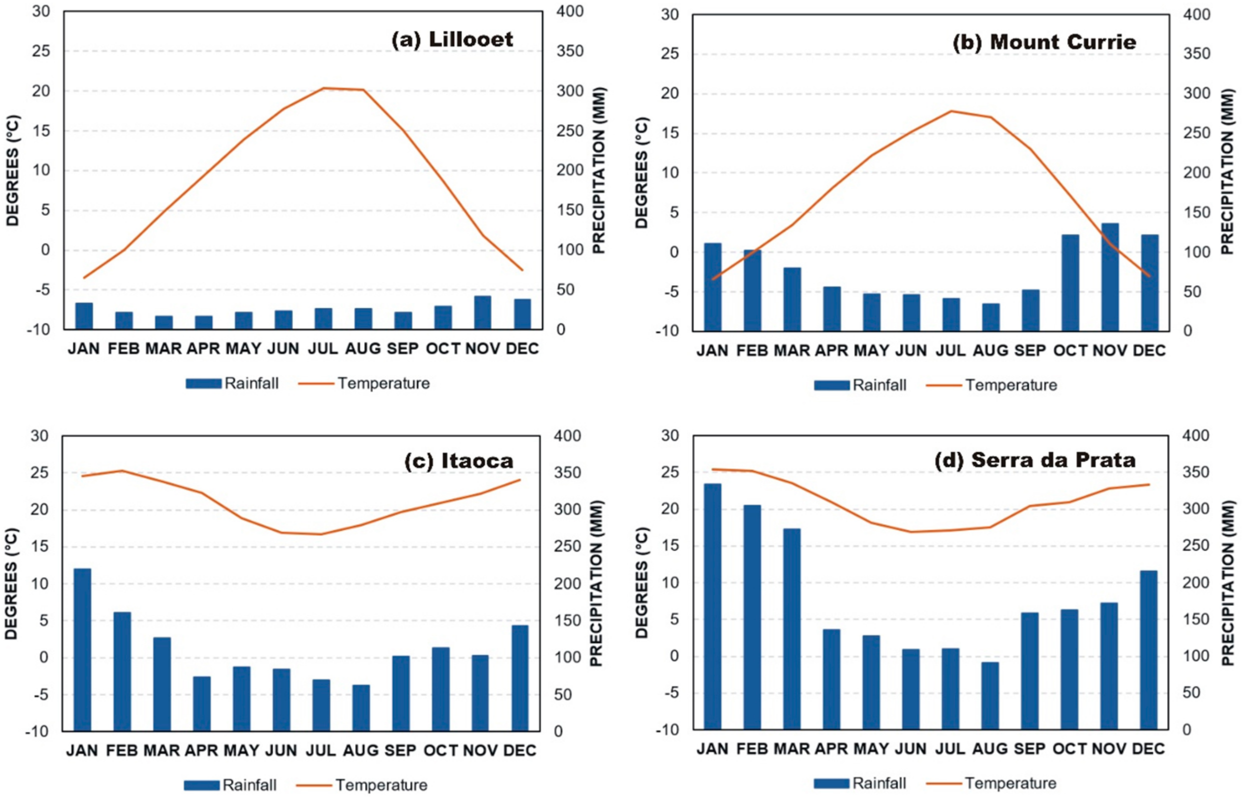
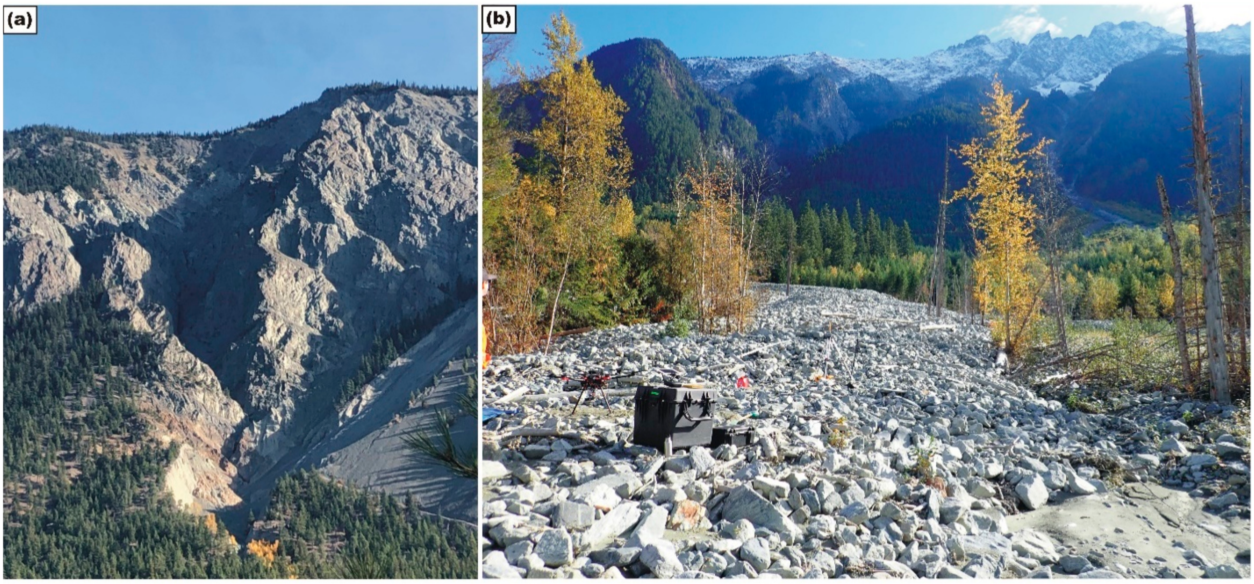


Figure 2. Multiannual rainfall distribution and mean temperature between 1971 and 2000 in (A) Lillooet, (B) Mount Currie, (C) Itaoca, and (D) Serra da Prata. Data were provided by the Pacific Climate Data Portal, (A and B) Station Lillooet Seton BCHPA, CIIAGRO and (C) Department of Water and Electricity of São Paulo (DAEE), and (D) Paraná Water Institute.



Source: courtesy of Sophia Zubrycky.
Figure 3. Study areas at (A) Lillooet Fountain North and (B) Mount Currie D.

flow-affected watersheds were visited, two in Brazil and three in Canada. The focus was on identifying the main characteristics related to debris flow activities in the geomorphology and stratigraphy of fan deposits. Sedimentological evidence of debris flows on the fan includes sorting, imbrication, levees, and buried logs. Similarly, in the transport zone, the presence of well-defined levees and large boulders that could not be moved by other flow-type processes such as floods can be signs of debris flows in an area (Johnson 1970, Costa 1984, Jakob 2005).

In Brazil, two watersheds were visited in the fall (July) and winter (August) of 2019: Guarda-mão (*GW*) and Tingidor (*TW*). Due to climatic conditions and the relatively low frequency of debris flows, vegetation growth began to cover the signs of debris flow activity. However, in the study areas, it was still possible to identify and map most of the features related

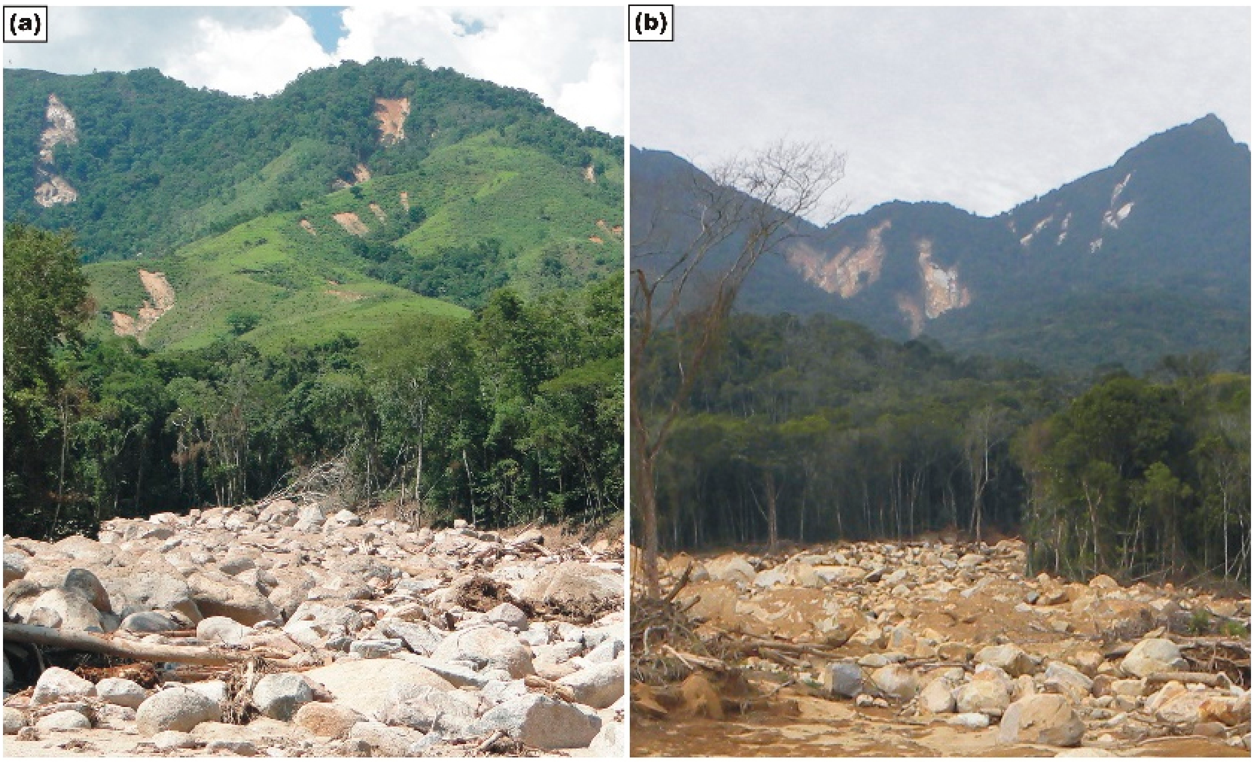


Figure 4. Study areas in (A) Itaoca and (B) Serra da Prata.

to debris flows. In comparison, at the sites in Canada, vegetation regrowth is not as fast as in a tropical environment, and the relatively high frequency of occurrence (Jordan 1994, Zubrycky *et al.* 2021) favors the identification and mapping of debris flow features. Three distinct watersheds were visited, namely, Fountain North (*FN*) and Fountain South (*FS*) in the fall (October) of 2019, and Mount Currie D (*MD*) in the summer (August) of 2020.

Morphometric parameters

Morphometric parameters have been used to study debris flows since the 1980s for a variety of applications, including susceptibility analysis and magnitude-frequency estimation (VanDine 1985, Johnson *et al.* 1991, Cenderelli and Steven Kite 1998, Gabet and Bookter 2008, Kovanen and Slaymaker 2008, Portilla *et al.* 2010, Chen and Yu 2011). Several authors have shown their usefulness for evaluating processes such as floods, debris floods, or debris flows (VanDine 1985, Slaymaker 1990, Johnson *et al.* 1991, Wilford *et al.* 2004, Welsh and Davies 2011, Ilinca 2021), and for identifying debris flow-prone watersheds when geomorphologic and stratigraphic evidence is not visible in the landscape (Welsh and Davies 2011, Ilinca 2021). Based on the literature, the following parameters were selected for analysis: area (A), drainage density (Dd), area > 25° (A25), relief ratio (Rr), length (L), basin Relief (Br), and Melton ratio (Mr) (Tab. 1).

In the literature, the *A* of a watershed has been related to the occurrence of debris flows. According to published studies in different parts of the world, small basins up to 10 km^2 are susceptible to debris flows (Slaymaker 1990, Scally *et al.* 2001, Ilinca 2021). The *Dd* has been related to how rapidly a watershed drains. A high value indicates a well-drained watershed, while a low value indicates a poorly drained watershed. Although not as commonly used as other parameters, the *Dd* contributes to the evaluation of debris flows, as a high value may indicate more intense hydrogeomorphologic processes such as floods, debris floods, and debris flows (Augusto Filho 1993). The *A25* provides the percentage of the watershed with a slope angle above 25°. As a gravity-induced process, an angle of 25° is suggested by many authors as the minimum slope to initiate debris flows (Costa 1984, VanDine 1996, Takahashi 2007). The *Br* may influence the intensity and reach of the debris flow (Nikolova *et al.* 2020). The *Rr* indicates the ruggedness of the watershed, which has been related to the production and availability of sediments. According to Scally *et al.* (2001), high ruggedness values indicate a watershed that is prone to more intense processes, such as debris flows. The *Mr* has been used to evaluate the watershed ruggedness and availability of sediments, as well as to evaluate the predominant hydrogeomorphologic processes in watersheds (Wilford *et al.* 2004, Welsh and Davies 2011, Ilinca 2021).

Topographic information was obtained from the *ALOS Palsar* Digital Elevation Model (DEM), with a 12.5-meter resolution (JAXA and EORC 2008). These data were chosen due to their availability worldwide so that data could be extracted from the same source for all sites. Although more detailed data are available, such as topographic maps and better resolution DEMs, especially for the Canadian sites, free data on the same scale for both areas are not available in Brazil, which could cause inconsistency in the results of the morphometric analysis. *ArcGIS 10.2* was used to automatically generate drainage paths for each DEM. Satellite images from *Planet* and *Google Earth* were referenced to manually correct the auto-generated drainage paths, for example, to remove duplicates.

Table 1. Description of morphometric parameters.

Morphometric Parameters	Abbreviation	Unit	Descriptions
Area	A	km^2	Planimetric area of the watershed
Drainage density	Dd	km/km^2	Total stream length divided by the watershed area
Area > 25°	A25	%	Percentage of the watershed area with a slope angle above 25°
Relief ratio	Rr	m/m	Basin relief divided by the watershed length
Length	L	km	Horizontal distance in a straight line between the upstream and downstream drainage limits.
Basin relief	Br	km	Difference between the higher and lower altitudes in the watershed
Melton ratio	Mr	DN*	Basin relief divided by the square root of the watershed area

*Dimensionless.

RESULTS

Debris flow deposits

The field surveys in the study areas show that all sites have features associated with debris flow activity, specifically local inverse grading, levees, and local lack of sorting. Specific observations of each of the study sites are shown in the following section.

The headwaters in the *FN* and *FS* watersheds feature steep slopes and an extensive sediment supply provided by the weathering of the sedimentary rocks in the catchment. Debris flows in the *FN* and *FS* watersheds form channels with levees reaching 2 m thick near the fan apex that lack sorting (Figs. 5A and 5B). Conglomerates and argillites are the most common type of clasts found in the deposits; the deposits are mostly composed of fine matrix particles smaller than 4 mm and cobbles and boulders (Jordan 1994, Zubrycky 2020) (Fig. 5C). On the lower slopes, the deposits indicate flow spreading and avulsions, including the transport of logs and the burial of trees by cemented matrix (Fig. 5D). Despite being located beside one another, the *FN* and *FS* watersheds show differences in textures and morphology, with deposits in the *FS* watershed being more uniform and coarser in comparison to the *FN* watershed, favoring the formation of prominent levees in the *FS* watershed (Zubrycky 2020).

The catchment area of *MD* is also steep, with an abundance of sediments, similar to the Lillooet site; however, the Mount Currie site is composed of granitic rocks. Debris flows in the *MD* watershed formed incised channels with levees reaching 15 m thick that lack sorting (Fig. 6A). Deposits are composed of large granite boulders, logs, and fine sediments that show local inverse grading (Fig. 6B). Compared to the *FN* and *FS* watersheds, debris flows in the *MD* watershed tend to remain more channelized, with spreading and avulsions further down the fan where channelization disappears (Zubrycky 2020).

Compared to the study sites in Canada, debris flows appear to be relatively rare in the long-term in Itaoca and Serra da Prata, and no records of other historical events exist (Brollo *et al.* 2015). The 2014 debris flow was triggered in *GW* by rainfall and the occurrence of shallow landslides, which provided initial sediments for transport. Igneous rocks, mostly granite, and fine sediments were identified in the deposits. Large boulders greater than 2 m in diameter were transported in the event (Figs. 7A and 7B). The debris flow in *GW* was mainly confined to the main V-shaped channel on higher slopes, losing confinement on the lower slopes and in the opening of the valley in the lowland, where spreading and deposition occurred; this spreading and deposition formed levees that are approximately 1.5 m thick with local inverse grading and local lack of sorting (Figs. 7C and 7D) (Gramani 2015, Dias 2021; Dias *et al.* 2022).

Similarly, the debris flow in *TW* (2011) was triggered by shallow landslides initiated by intense rainfall, and no historical records of previous occurrences at the site exist (Dias *et al.* 2022). The deposits are mostly composed of granite, with fine sediments and the presence of logs (Fig. 8A), and large boulders more than 2 m in diameter (Fig. 8B). The debris flow in *TW* was primarily confined; however, the channel lost confinement at several locations, forming deposits along the channel before reaching lowland areas and spreading near the river at the maximum runout. Levees reaching 2 m thick were formed beside the channel in depositional areas with the presence of local inverse grading and local lack of sorting (Figs. 8C and 8D) (Dias 2021, Dias *et al.* 2022).

Morphometric parameters

The results show that morphometric parameter values may differ depending on the area (Tab. 2). The values of watershed *area (A)* range from 0.4 to 3.74 km^2. For the watersheds in Serra do Mar (n = 2), values range from 2.02 to 3.74 km^2, and for the watersheds in British Columbia, (n = 3), values range from 0.4 to 1.36 km^2. The *Dd* values show a different relation, ranging from 3.44 to 5.75 m/km^2; they do not show the same distinction as the previous parameter, indicating watersheds with similar values in both environments. *A25* ranges from 22.1 to 94.7%, with higher values presented by *FN*, *FS,* and *MD* (with values ranging from 86 to 93.6%) in comparison to *GW* and *TW* (with values between 22.1 and 33.5%), indicating one of the most extreme differences among all the parameters.

The results of the *Rr*, *L*, *Br*, and *Mr* parameters have the same distinction as observed in the *A* and *A25* values, with *Rr* values ranging from 0.23 to 0.75. *FN*, *FS*, and *MD* have higher values (ranging from 0.65 to 0.75) than *GW* and *TW* (with values of 0.23 and 0.25). An inverse relation is observed for *L*, with watersheds in Canada showing low values (ranging from 1.63 to 2.19 km) compared to Brazil (with values between 3.18

Figure 5. (A and B) Debris flow deposit composed of argillites and (C) lobes and (D) levees at Fountain North in Lillooet.

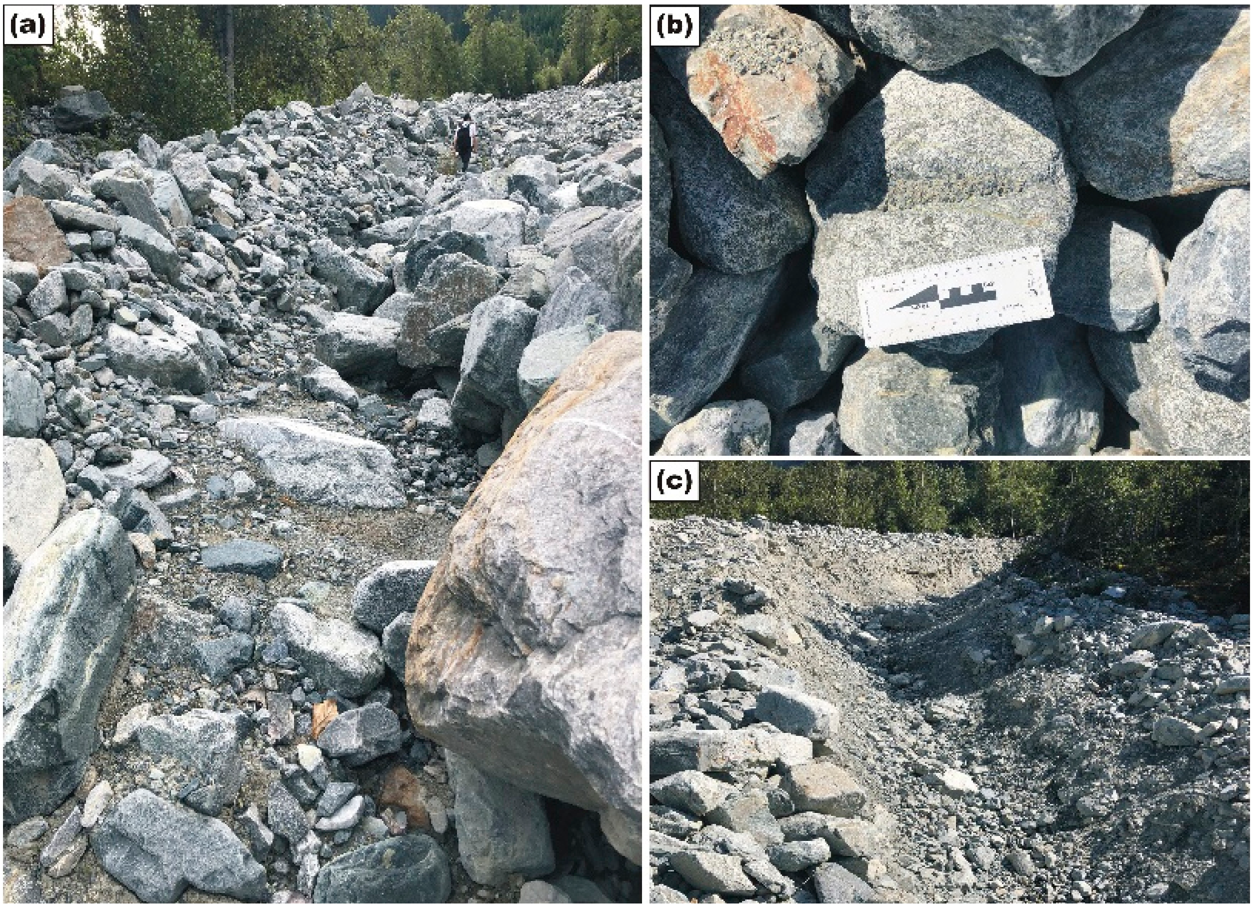


Figure 6. (A and B) Debris flow deposit composed of granite and (C) levees at Mount Currie D.

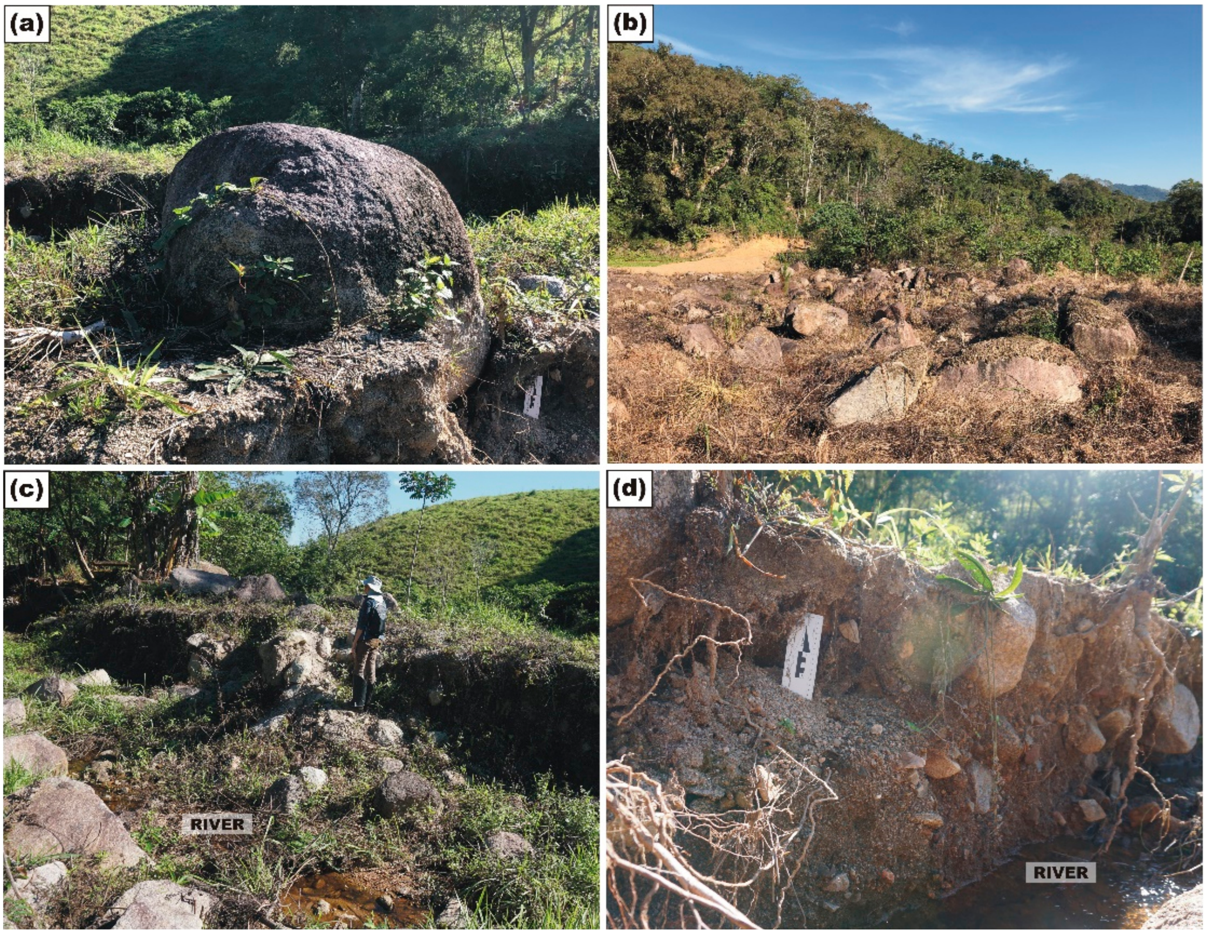


Figure 7. (A and B) Debris flow deposit composed of granites and (C and D) levees in the Guarda-mão watershed in Itaoca.

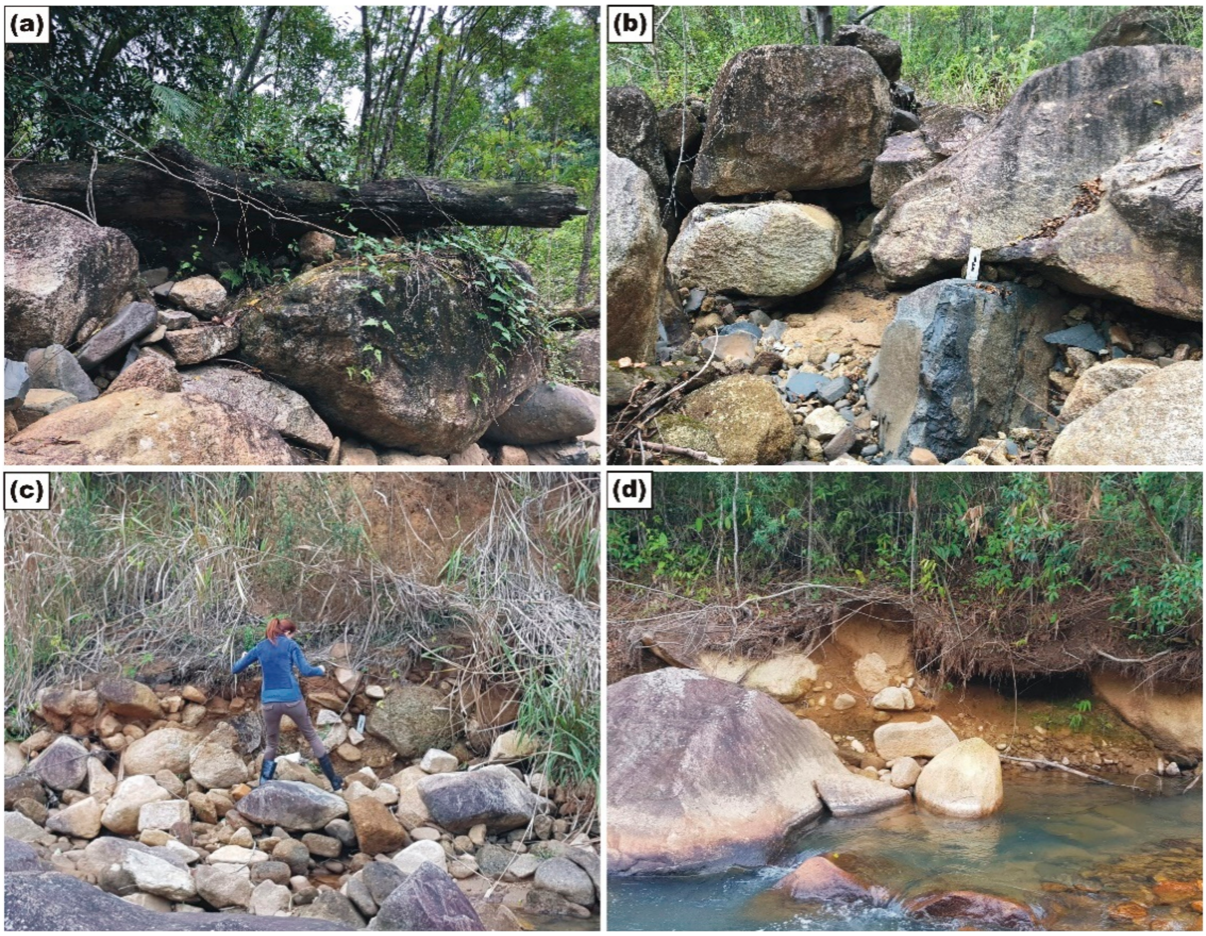


Figure 8. (A and B) Debris flow deposit composed of granites and (C and D) levees in the Tingidor watershed in Serra da Prata.

Table 2. Descriptive statistics of the morphometric parameters.

Parameters	Canada			Brazil	
	FN	FS	MD	GW	TW
Area (km²)	0.9	0.4	1.36	3.74	2.02
Drainage Density (km/km²)	4.72	3.75	3.44	5.75	4.45
Area > 25° (%)	86	88.6	93.6	33.5	22.1
Relief ratio (m/m)	0.65	0.69	0.75	0.23	0.25
Basin length (km)	1.76	1.63	2.19	3.18	3.3
Basin relief (km)	1.15	1.139	1.65	0.753	0.83
Melton ratio (DN)	1.22	1.8	1.42	0.39	0.58

and 3.33 km). Values for *Br* range from 0.75 to 1.65 km, and although there was not a large variation among them, *FN*, *FS*, and *MD* have high values (ranging from 1.15 to 1.65 km) in comparison to *GW* and *TW* (with values of 0.83 and 0.75). Lastly, the *Mr* values range from 0.39 to 1.8, and, similar to *Br*, there was not a large variation among *Mr* values; however, the watersheds in Canada distinctly have high values (ranging from 1.22 to 1.80) in comparison to the Brazilian watersheds (with values 0.39 and 0.58).

DISCUSSION

Debris flow deposits and comparison with occurrences worldwide

Debris flows occur in different parts of the world; they have some similarities globally but have different characteristics due to local watershed morphometries and climate. Although the rainfall values are relatively low at the Canadian sites, especially in the *FN* and *FS* watersheds, the recurrence of events suggests that constant sediment availability contributes to triggering debris flows, which can indicate a transport-limited or supply-unlimited system. In comparison, the Brazilian sites have a high mean annual precipitation, and the lack of other debris flows recorded in the *GW* and *TW* may suggest limited sediment availability, indicating a weathering-limited or supply-limited system.

As stated by Jakob (2005), in a supply-limited watershed, it may be difficult to identify the occurrence of debris flows due to low frequency. In *GW* and *TW*, the events from 2014 and 2011 are the only historical records of recent debris flows in these areas (for the past 100 years), which suggests a low frequency of the debris flow process. The characteristics of the tropical environment also make it difficult to identify paleo-deposits, as the regeneration of dense, tropical rainforest vegetation is extremely fast. Even for the recent occurrence in *GW* in 2014, the identification of the main deposit features in the field was possible due only to fires caused by human activity that occurred just before the site visit in the area. Additionally, debris flows in Brazil are recorded when they affect occupied areas and cause casualties, which may influence the frequency evaluation. Another problem is the availability of annual aerial photographs for the areas, which makes it difficult to verify occurrences over the years. In comparison, in the study areas in Canada, the combination of historical records of several occurrences and the availability of aerial and satellite photographs makes it possible to identify and map multiple deposits and affected areas.

Although the total number of events may be underreported, because multiple events could have happened between image collections and smaller events may not be visible in the images, the identification of deposit features in the field in the long-term tends to be easier in the *FN*, *FS*, and *MD* watersheds, in contrast to *GW* and *TW*; this contrast is mostly due to differences in the time that it takes for the vegetation to regenerate, which tends to be quicker in a tropical environment as a consequence of the climate. The geomorphic evidence of debris flows agrees with the main characteristics pointed out by Costa (1984), Jakob (1996), Johnson (1970), and VanDine (1996) and a worldwide register of debris flow-affected areas, which includes some occurrences in South America (García-Martínez and López 2005, García-Delgado *et al*. 2019), Europe (Rickenmann and Zimmermann 1993, Breien *et al*. 2008, Stoffel 2010, Ozturk *et al*. 2018, Ilinca 2021), Asia (King 1996, Cui *et al*. 2013), Oceania (Pierson 1986), and North America (Jackson *et al*. 1987, Gabet and Bookter 2008, Riley *et al*. 2013, Kean *et al*. 2019). The main features present at all sites were levees and local lack of sorting, followed by the presence of local inverse grading and very large boulders. The presence of large boulders in the *GW*, *TW*, and *MD* watersheds may be associated with geological and lithological differences between the *FN* and *FS* watersheds. While the Lillooet area has a predominance of highly jointed sedimentary rocks, Itaoca, Serra da Prata, and Mount Currie have a prevalence of more massive igneous and metamorphic rocks (Fig. 9).

Morphometric parameters and comparison with values from sites worldwide

Regarding morphometric parameters, the literature features the use of *A*, *Rr*, *L*, *Br*, and *Mr*, with published studies in different parts of the world, particularly in North America (Canada and USA), Europe (Italian Alps, Bulgaria, and Romania), Asia, and Oceania (Taiwan and New Zealand), and some studies in South America (Brazil and Puerto Rico) (Tab. 3). The results obtained in this paper show similarity with published data and their variations, considering, especially, the climate (Fig. 10).

The *A* parameter is one of the most commonly used parameters for the evaluation of debris flow occurrence. The results for *A* show that, although the values are slightly smaller at the sites in Canada than at the sites in Brazil, they are within the typical range for debris flow watersheds evaluated in other areas. The Canadian sites are below the median for Temperate zones, and the Brazilian sites are above the median for Tropical zones (Fig. 10A). Although small areas are considered debris flow prone, the intensity of the process may vary depending on the size of the watershed, and as stated by Ilinca (2021), larger watersheds may be more prone to host debris floods. Both occurrences in Brazil initiated as debris flows, but after initial deposition, the processes continued to low-relief areas,

Figure 9. Debris flow deposits in (A) Lillooet, (B) Itaoca, (C) Mount Currie, and (D) Serra da Prata.

turning into debris floods and destroying the city center, which did not occur at the sites in Canada, where the process was restricted to the watershed as a debris flow.

The *FN*, *FS,* and *MD* sites had high *Rr* values compared to the *GW* and *TW* sites (maximum 0.75 versus 0.25, respectively), which suggests that the watersheds are more prone to intense processes and have greater availability of sediments. The distinct *Rr* values may contribute to differences in the frequency of debris flows in the watersheds. The *MD* watershed had the highest value (0.75) and number of occurrences (19), as mapped by Zubrycky *et al.* (2021), which suggests it is the site that is most prone to debris flows. Values obtained by Jakob (1996) for weathering-limited basins and transport-limited basins also show this variance. Despite presenting similar mean and maximum values, the minimum value for the weathering-limited type was low in comparison to the transport-limited type (0.27 versus 0.38, respectively) (Jakob 1996). Other sites with the occurrence of debris flows also showed this variance in *Rr* values, particularly the North Cascades in the USA (0.01 to 0.58) (Kovanen and Slaymaker 2008), the Pyrenees Mountains in Italy (0.22 to 0.51) (Portilla *et al.* 2010), and Taiwan (0.20 to 0.44) (Chen and Yu 2011). In comparison to the distribution of data from the literature, the values for the Canadian sites are outside of the range of those for Temperate zones, while for the Brazilian sites, the values are above the median values for Tropical zones (Fig. 10B).

Whereas the *L* values at *FN*, *FS,* and *MD* are within the range of values suggested by Welsh and Davies (2011) for debris flow areas (up to 2.7 km), the watersheds in Brazil have values above this limit (3.18 and 3.3 km). Other affected areas worldwide also show high *L* values, such as North Fork Mountain in the USA (1 to 4.28 km) (Cenderelli and Steven Kite 1998); British Columbia, Canada (0.28 to 4.68 km) (Wilford *et al.* 2004); New Zealand (1.05 to 4.5 km) (Scally *et al.* 2010); and Taiwan (1.54 to 5.75 km) (Chen and Yu 2011). Among the 72 sites evaluated by Ilinca (2021), only one watershed associated with debris flows had a length greater than 1.7 km (2.78 km), which, according to the author, may indicate that although these sites can be affected by debris flows, debris flood and flood processes may be more frequent. Considering the results by climate zones, *MD* is close to the median value and *FN* and *FS* are below 25% of the results for Temperate, while the values for *GW* and *TW* are close to the maximum considering the distribution for Tropical zones (Fig. 10C).

Unlike *L, Br* values did not show a high variance among the sites; however, *FN*, *FS*, and *MD* had the highest values, which may contribute to the high frequency of occurrences in comparison to *GW* and *TW* sites. Values reported in the literature are similar to the results in this research (Tab. 3), with higher values in British Columbia, Canada (> 2 km) (Jakob 1996) and New Zealand (1.9 km) (Scally *et al.* 2010), and the lowest values in Puerto Rico (0.13 to 0.25 km) (Coe *et al.* 2021).

Table 3. Comparison of parameter values at different sites.

Source	Area (km^2)	Relief ratio (m/m)	Length (km)	Basin relief (km)	Melton ratio	Location
Jackson *et al.* (1987)	----	----	----	----	0.25 to 0.30	Alberta, Canada
Slaymaker (1990)	0.4 to 7	----	----	----	----	British Columbia, Canada
Marchi *et al.* (1993)	0.20 to 14	----	----	----	0.49 to 1.74	Italian Alps, Italy
Jakob (1996)	0.3 to 14.4	0.27 to 0.76	----	0.73 to 2.06	----	British Columbia, Canada
Cenderelli and Steven Kite (1998)	1.78 to 17.47	0.35 to 0.49	1 to 4.28	----	----	North Fork Mountain, USA
Scally *et al.* (2001)	0.05 to 10.90	----	----	0.31 to 1.36	0.38 to 1.77	British Columbia, Canada
Marchi *et al.* (2002)	4.1			1.15		Italian Alps, Italy
Wilford *et al.* (2004)	0.2 to 4.1	0.3 to 0.49	0.28 to 4.68	0.6 to 1.4	0.66 to 1.21	British Columbia, Canada
Gabet and Bookter (2008)	0.08 to 0.76	----	----	----	----	Montana, USA
Kovanen and Slaymaker (2008)	0.29 to 32.9	0.01 to 0.58		0.58 to 1.2	0.15 to 1.07	North Cascades foothill, USA
De Scally *et al.* (2010)	0.18 to 9.66	0.25 to 0.88	1.05 to 4.5	0.55 to 1.93	0.45 to 1.59	New Zealand
Portilla *et al.* (2010)	0.029 to 3.76	0.22 to 0.51	----	0.29 to 1.42	0.45 to 2.91	Pyrenees Mountain, Italy
Welsh and Davies (2011)	----	----	< 2.7	----	> 0.60	New Zealand
Chen and Yu (2011)	0.51 to 8.63	0.20 to 0.44	1.54 to 5.75	----	----	Taiwan
Simoni *et al.* (2011)	0.28 to 9.40	----	0.9 to 3.9	----	----	South Tyrol, Italy
Dias *et al.* (2016)	24 and 20	0.07 and 0.13	----	----	----	Serra do Mar, Brazil
Picanço *et al.* (2016)	1.03 to 3.06	----	1.99 to 3.71	0.66 to 1.11	0.41 to 0.78	Serra do Mar, Brazil
Dotseva and Gerdjikov (2020)	1.52 to 3.76	0.05 to 0.68	----	----	0.54 to 0.73	Stara Platina Mountains, Bulgaria
Nikolova *et al.* (2020)	0.015 to 39.27	0.05 to 0.68	0.33 to 15.50	0.16 to 0.82	0.13 to 1.59	Eastern Rhodopes, Bulgaria
Ilinca (2021)	0.005 to 1.02	Mean 0.56	< 1.7	----	> 0.55	Southern Carpathians, Romania
Coe *et al.* (2021)	0.094 to 0.25	----	----	0.13 to 0.25	0.53 to 0.87	Puerto Rico
V.C. Dias *et al.* (2021)	----	0.07 to 0.11	----	----	----	Serra do Mar, Brazil
This paper	0.9 to 1.36	0.65 to 0.75	1.63 to 2.19	1.15 to 1.65	1.22 to 1.8	British Columbia, Canada
This paper	2.02 and 3.74	0.23 and 0.25	3.18 and 3.3	0.75 and 0.83	0.39 and 0.58	Serra do Mar, Brazil

Despite having very similar mean values for weathering-limited and transport-limited basins, the latter has a higher value (2.06 km) in watersheds evaluated by Jakob (1996), similar to the *FN*, *FS*, and *MD* sites, which may favor the recurrence of the processes at these sites. In Europe, values are more similar to those of the *TW* and *GW* sites, with values ranging from 0.16 to 0.82 km in Bulgaria (Nikolova *et al.* 2020) and from 0.20 to 1.42 km in Italy (Portilla *et al.* 2010). Considering climate zones, values in *FN*, *FS*, and *MD* are above 75% of the values for Temperate zones, while values in GW and TW are above the median but under 75% of the sample (Fig. 10D).

The *Mr* is largely used as an indicator of debris flows in small watersheds, particularly since the 2000s. Welsh and Davies (2011) stated that values above 0.60 indicate watersheds with a predominance of debris flows, while values between 0.30 and 0.60 indicate a predominance of debris floods and floods. The results show that the watersheds in Canada have values characteristic of debris flow-prone watersheds (1.22 to 1.8), including those outside of the distribution for Temperate zones. In contrast, the areas in Brazil are below the limit established by Welsh and Davies (2011) (0.39 and 0.58); in other words, they are not classified as having debris flows as a major process but are still in the range of values for cases in Tropical zones (Fig. 10E). Nevertheless, other regions worldwide with the occurrence of debris flows have *Mr* values below 0.60, such as Italy (0.45 to 2.91) (Marchi *et al.* 1993, Portilla *et al.* 2010), New Zealand (0.45 to 2.91) (Scally *et al.* 2010), Bulgaria (0.13 to 1.59) (Nikolova *et al.* 2020), Puerto Rico (Coe *et al.* 2021), and even Canada and the USA (0.25 to 0.30 and 0.15 to 1.07, respectively) (Jackson *et al.* 1987, Kovanen and Slaymaker 2008). Taking into account the results from previous morphometric parameters, this difference may indicate that, although debris flows occur in watersheds with values below 0.60, they are not the main process and have reoccurred less frequently. In this way, attributes from *FN*, *FS*, and *MD* indicated an area with debris flow as a dominant process, while results from *TW* and *GW* indicated areas with a mixed process, highlighting debris flows and debris flood.

The *Dd* and *A25* parameters are not as widely used as the other parameters discussed above; however, values from the

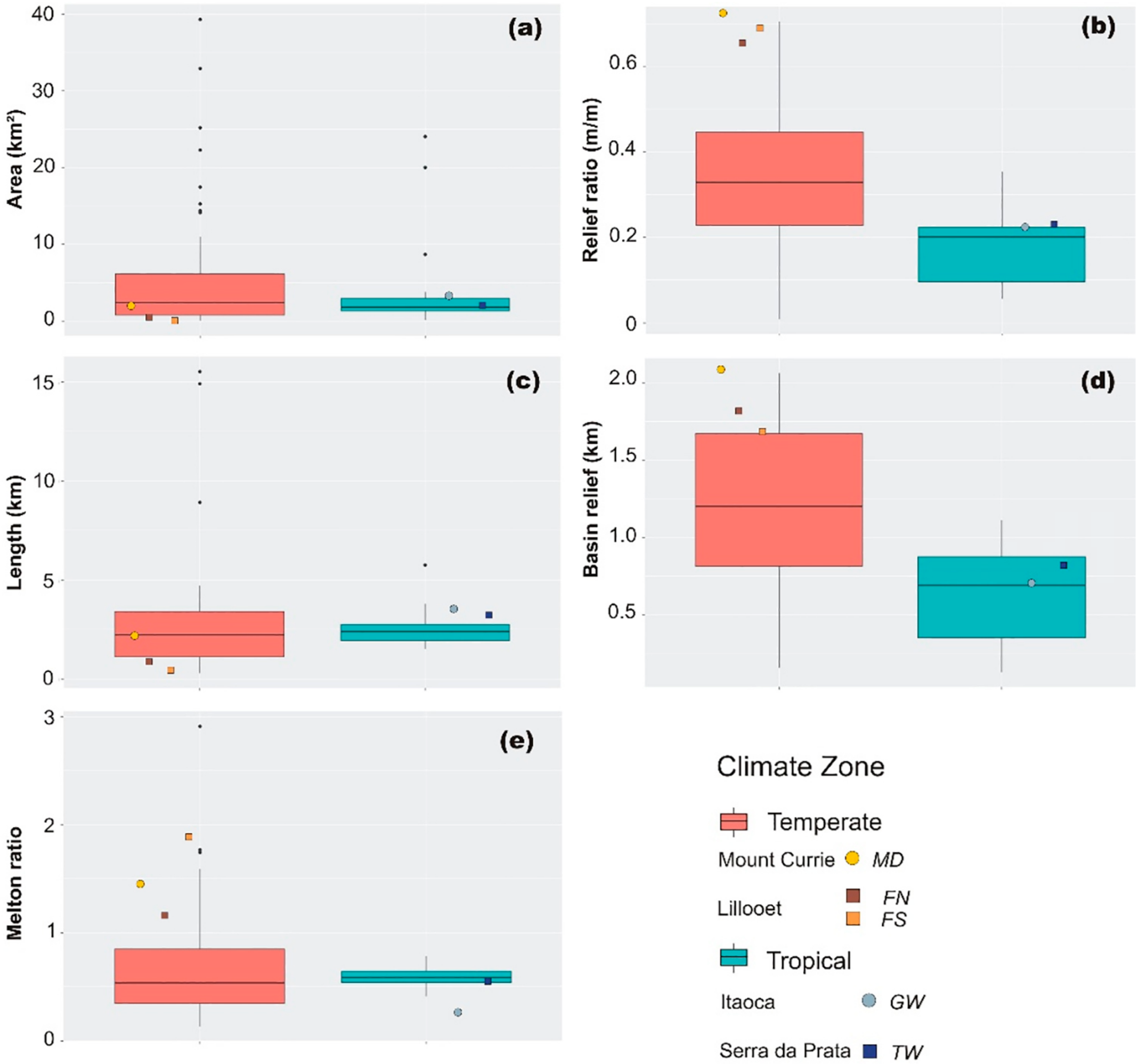


Figure 10. Boxplot of parameters from Tab. 3 categorized by climatic zone.

sites in Canada and Brazil also contribute to understanding differences in debris flow occurrences in these areas. Regarding *Dd*, the results in Tab. 2 indicate well-drained watersheds, particularly the *FN* and *GW* sites, which have high values (4.72 and 5.75 km/km^2). In British Columbia, Canada, Jakob (1996) found values between 0.6 and 6.8 km/km^2 in weathering-limited basins and 2.1 and 7.4 km/km^2 in transport-limited basins. Cenderelli and Steven Kite (1998) divided the watersheds according to debris flow zones and found higher values for *Dd* in failure zones (5.62 to 12.40 km/km^2), followed by values in transport zones (2.57 to 4.44 km/km^2) and deposition zones (2.67 to 4.36 km/km^2) in the USA. The high values in failure zones indicate the need for a well-drained area for the initiation of the process. Despite showing lower values in comparison to previous examples (1.57 to 2.12 km/km^2), which indicates poor to moderate drainage, watersheds evaluated by Dotseva and Gerdjikov (2020) also have debris flows, which may indicate the influence of other morphometric features.

All sites in Canada have values higher than 85% for *A25*, which indicates extremely steep watersheds, in comparison to values found at the Brazilian sites (22.1 and 33.5%). This difference may influence the recurrence of events in the areas, with more frequent events occurring due to the availability of sediments to transport in the *FN*, *FS*, and *MD* sites compared to the *GW* and *TW* sites. This difference in the percentages of watersheds with high-angled areas was also observed in other studies. In affected areas in Bulgaria, Nikolova *et al.* (2020) use the percentage of watersheds above 30 and 45 degrees as a parameter, with results between 1.28% and 74.1%. Likewise, Coe *et al.* (2021) evaluated watersheds in Puerto Rico using areas above 30° as the limit, obtaining results between 54 and 62%. Similar to *Dd*, this variability among the results in different areas may indicate the influence of other morphometric characteristics in controlling debris flow occurrences in watersheds.

CONCLUSIONS

This study compared watersheds affected by debris flows in two different environments through field surveys, geomorphic characterization using morphometric parameters, and comparing results from occurrences worldwide. Despite significant differences in geology and climate, the study areas had similar main debris flow features and morphometries. Although the watersheds in Brazil had some morphometric variations from the literature values that are characteristic of debris flow-prone areas, other studies showed results in agreement with the values shown here. This may indicate variability in the morphometric characteristics of a watershed concerning the occurrence of debris flows.

Despite having a high average annual rainfall in comparison to areas in Canada, a single debris flow occurrence in the historical record in each of the watersheds in Brazil suggests a weathering-limited system. In this way, regardless of the higher amounts of precipitation, sediment recharge may take more time than in the transport-limited systems observed in the temperate watersheds. This characteristic, in addition to the lower values for *A25* (33.5 and 22.05), *Rr* (0.23 and 0.25), and *Mr* (0.39 and 0.58), may contribute to the differences in the recurrence of debris flows.

However, it is important to point out the need for more studies about debris flow occurrences in Brazil, specifically regarding morphometric analyses and physical characterization of affected areas, considering slope, soil type, soil thickness, degree of weathering, and hydrogeology. This characterization should ideally be made immediately after the event takes place, aiming for an accurate analysis of the process, adding more data for comparison with future occurrences and for comparison with other events worldwide. The monitoring of susceptible areas using remote sensing, aerial photos, and rainfall intensity, is needed to provide more data about debris flow processes in Brazil. Also, it is necessary to improve rainfall measurement in susceptible areas, such as Serra do Mar, providing more information about rainfall thresholds that trigger debris flow events. Despite the limitations and lack of historical data, this study contributed to the understanding of debris flows in Brazil by comparing deposit features and morphometric characteristics with those found in affected areas in Canada. The similarities and differences between the areas can help develop future studies about debris flows in Brazil, especially considering data availability limitations.

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Data availability statement

The raw data required in this study are available upon request by contacting V. C. Dias (vivian.cristina.dias@alumni.usp.br).

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