Morphological characteristics of drainage networks related to landslide cluster in the Colombian Andean

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Abstract. Debris flows are a highly destructive and common phenomena in Colombia. A large percentage are triggered during seasonal rainfalls. And the Andean region is the most affected area, which exhibits a dynamic landscape made up of weak and highly weathered materials and affected by tectonic stress. As a result of this setting, sometimes many landslides are generated in clusters. Those hillslope landslides are the sediment source for the formation of debris flows. The main goal of this study is to know the state of the dynamics of 3 basins that have been affected by cluster landslides and their subsequent debris flows that have occurred in the northern region of the Colombian Andes using diverse morphometric indices. In general terms, the results show a transitory state into basins, with an evident migration along the margins of the network drainages due to unbalance state. This means more susceptible areas with greater geomorphodynamic activity.

1 Introduction

Debris flow is defined as a phenomenon with very rapid to extremely rapid mobility, according to water content, sediments, and topography [1], [2]. Debris flows are common and highly destructive in tropical and mountainous environments like Colombia. In 30.730 compiled records, there were 138.290 people affected; 34.198 deaths, and economic losses of 654.517.292 (USD). In addition, it is indicated that 87% of landslides are triggered by rainfall [3].

Debris flows are formed generally from shallow - translational - landslides triggered by rainfall. The occurrence is favored by a dynamic landscape made up of weak and highly weathered materials and affected by tectonic stress. Landslides are triggered by the imposition of body forces on hillslope materials. One of these forces comes from relative base-level fall which occurs in most active montane landscapes and provides a sufficient condition for long-term hillslope erosion [4]. Morphology landscape reflects the interaction between Earth's surface geomorphological processes, rock, and soil. Longitudinal profiles of rivers retain an interpretable signature of tectonic forcing and landslide erosion rates can match high rates of landscape denudation [5], [6].

Sometimes during strong and/or prolonged rainfall events, a large number of landslides are generated from tens to hundreds (cluster), in the same rain event and within a limited time and area; these events are called "Multiple-occurrence regional landslide events" [7]. Those hillslope debris flows are the sediment source for the formation of debris flows, called in Colombia as "*Avenidas Torrenciales"*. Those are described as a mixture of water and sediment in different proportions, moving rapidly along channels in small and mountain basins [8]. The availability of sediment on the hillslopes and bottom of streams may be increased due to its location in a tectonically active zone generating uplift processes, rejuvenation of landscape, and reorganization of drainage [9]–[13].

In this study, the objective is to know the state of the dynamics of the basins of interest where cluster landslides and their subsequent torrential flows have occurred using diverse morphometric indices to survey drainage rearrangement.

2 Study area and data

The Colombian Andean is the most affected region by landslides during bimodal seasonal rainfalls. In the northern Andes, there have been some cluster-type events with a subsequent debris flow. Some records have occurred in the municipality of San Carlos (1990), Tarazá (2007), Salgar (La Liboriana - 2015), Yalí (2020), Anorí (2020), Dabeiba (2020) and Santo Domingo (2021). The study area focuses on the basins associated with the events cluster shown in Figure 1; San Carlos into the Nare basin, Salgar into the San Juan basin and Dabeiba into the Riosucio basin.

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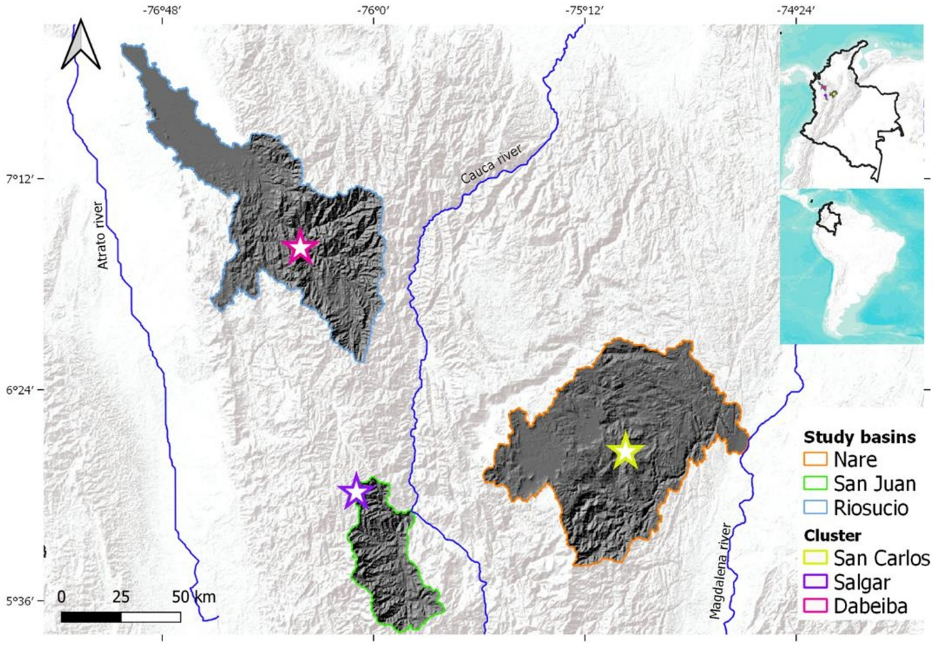

Fig. 1. Study area.

Table 1 shows the number and frequency of drains analyzed for each basin. In San Carlos, the largest number of landslides and economic damage to infrastructure occurred. However, the cluster event in the municipality of Salgar caused the highest damage to the population (104 deaths).

Table 1. Data study area.

Basin/ Municipality Cluster	N° Landslides	N° Deaths
Ríosucio/ Dabeiba El Mohan	~170	5 [16]
San Juan/ Salgar La Liboriana	~160 [15]	~100 [17]
Nare/ San Carlos La Arenosa	699 [13]	20 [18]

3 Geomorphic indices

Morphometry is the measurement and mathematical analysis of the configuration of the Earth's surface. A river basin is the fundamental geomorphic unit in which important information is found regarding its formation and evolution. This stored information is key to understanding geomorphic activity.

Indices are commonly used to visualize and quantify changes in morphometry, dynamics and evolution of drainage networks of basins. We use three indices to identify possible correlations between changes in the drainage network and cluster events. Those include Hack index (SL), integrated position function in the drainage network (χ) and Normalized channel steepness index (Ksn).

SL index is based on detecting abrupt variations in slope angle of the longitudinal profile of rivers caused by an anomaly (knickpoint). It is generally very sensitive to changes in slope and it is applied to assess relationships between possible tectonic activity, rock strength and topography.

χ parameter represents a solution for the stream power law equation. Characterizes drainage topology and geometry, it is sensitive to changes in upstream areas. Calculating χ to drainage networks and comparing values at a watershed divides, produce a snapshot of dynamic remodeling of drainage basins. Another application is the transformed longitudinal profiles (χ plots), which allow the comparison of profiles independent of spatial scale.

The slope of the χ- elevation plot is the Ksn index which has the main objective to highlight any external factor that deviates the river profile from an equilibrium state into a transient state.

4 Discussion and results

Colombia is a complex multi-hazard scenario [14]. Some areas are more susceptible than others according to geological, geomorphological, and hydrological settings. It is essential to understand why those areas are more susceptible or have more active morphodynamic processes than others, apparently similar.

Figure 2 and Figure 3 show the longitudinal profile of the main drainage with the distribution of slope and SL index values on the right and left lateral sides of the stream; top and bottom in Figure. In the three basins, it is observed an unusual distribution of high slopes, as it is expected that high values will be in the upper part of the basin, in this case, the high slope values are distributed along the drainage, also reflected in both sides of the basin. The distribution of SL values (Figure 3) is not uniform along the riverbed. High values are found in the middle part of the Nare and Sucio river basins, while the highest values in the San Juan river are concentrated in the final part of its way. There is no relationship between the distribution of SL index values and the presence of clusters.

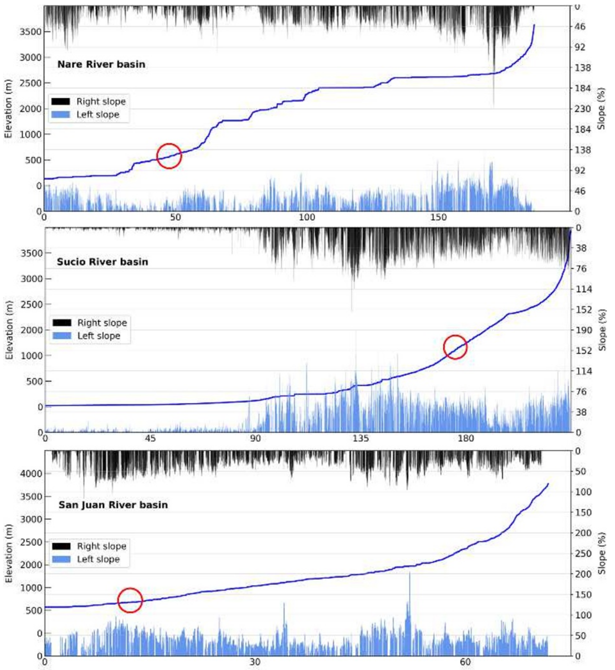

Fig. 2. Longitudinal profiles with slope values on both margins of the main drainage. The red circle represents local basin associated with the cluster type event.

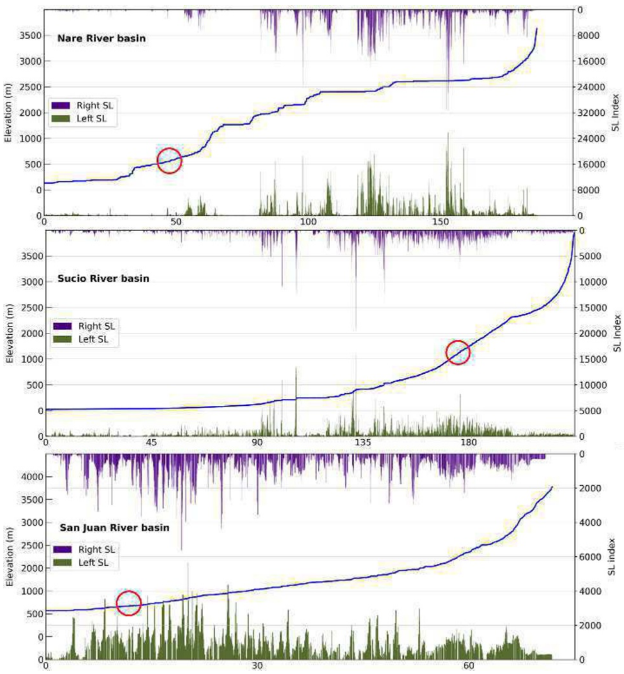

Fig. 3. Longitudinal profiles with SL index values on both margins of the main drainage. The red circle represents local basin associated with the cluster type event.

Figure 4 shows distribution of the χ-index in drainage network. Indicated with a red circle the local basin associated with the cluster type event. In the areas close to the cluster events analyzed, high values of the chi index are observed in the drainage network.

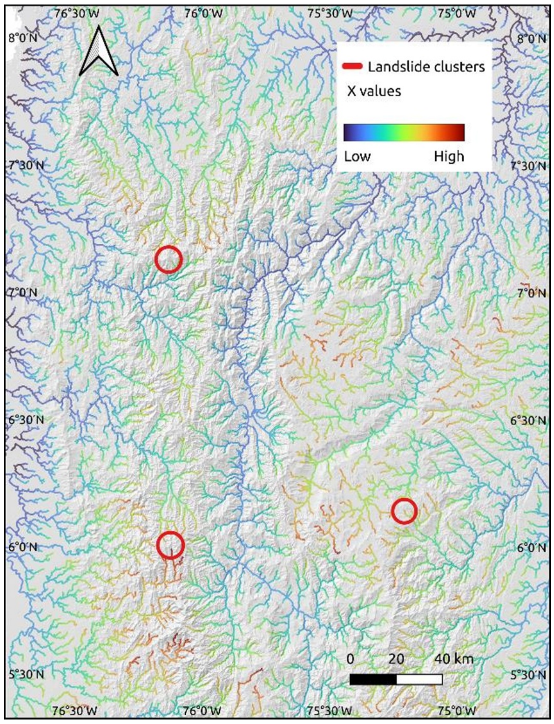

Fig. 4. χ map with cluster landslide in red circle.

Figure 5a, 5b and 5c show χ-plots for each basin. The presence of disturbances within the basins can be observed, expressed in high values of the variable Ksn (> 2.8). Figure 5d shows fluvial network reorganization represented in the movement of divides of the basins towards high values of the χ index (see the direction of arrows).

In the Nare River basin on the western and northern sides, there is a reduction of catchment area as a result of the advance of the watershed divides (see [19]). In the Sucio River basin, the divide advances in an East-West direction with implications of loss in the area; the opposite is the case in the northern boundary where the divide is gaining area from the neighboring basin. These patterns are reflected in Figure 5a y Figure 5b. The approximate location of the local tributary where each of the cluster events occurred is indicated by a black dot (Dabeiba y San Carlos).

In both cases, the affected drainages would be under the condition of loss of area. Regarding the San Juan river basin, the advance of the watershed is in an East-West direction as a way of gaining area over the neighboring basin. The location of the Salgar cluster event would be influenced by the presence of knickpoints within nearby higher-order drainage systems (Figura 5c).

In the basins where the cluster-type events occurred, the χ showed a transitory state, with an evident unbalance in the margins of the drainages presenting that they are migrating. This means more susceptible areas with greater morphodynamic activity.

Having a better compression of morphodynamics from morphogenesis is important to assess landslide and debris flow susceptibility conditions regarding

https://doi.org/10.1051/e3sconf/202341505015

landscape characteristics and evolution. In addition, a general characteristic of this type of event is the subsequent torrential flow, hence the importance of deepening the determination of morphometric indices that delve into determining the torrentiality of the basins as an additional analysis to the knowledge of the morphodynamic processes that have occurred in it.

The results of the indices were not strongly correlated with the occurrence of cluster events. In future research, a more detailed scale analysis is needed in the local watersheds where cluster events occurred. It is also necessary to carry out analyses in basins with and without the presence of clusters to obtain a better comparative analysis.

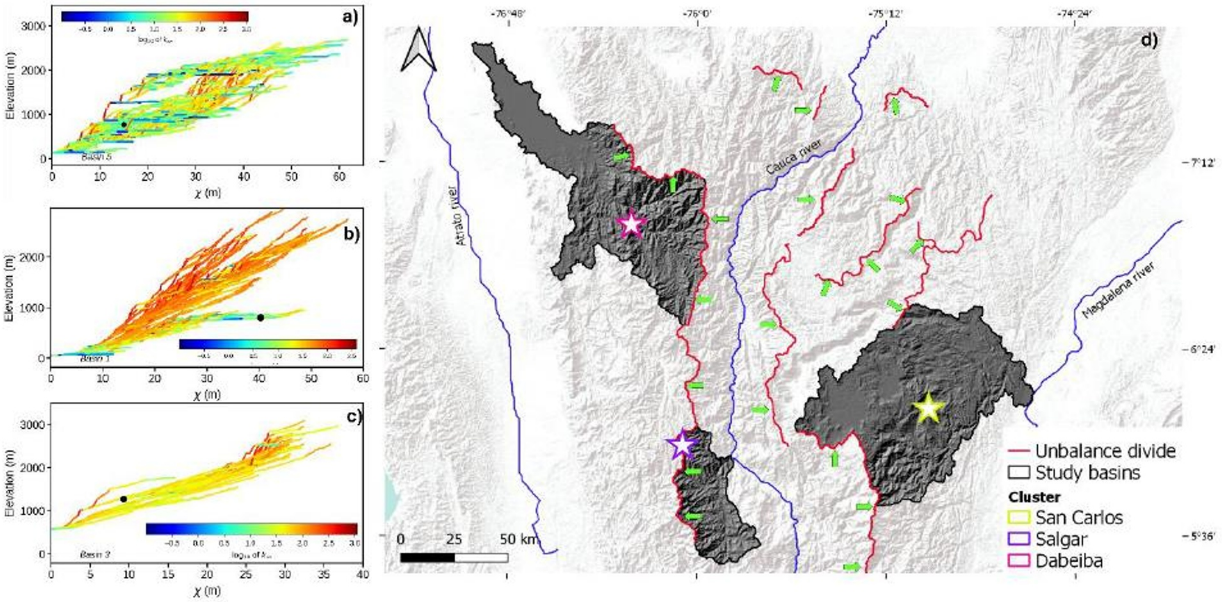

Fig. 5. Morphometric indices. a) χ plot Nare River b) χ plot Sucio River c) χ plot San Juan River d) Unbalance divides around study basins.

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