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Hydrological similarity of catchments in the southern area of Colombian Andean region

G A Carrillo-Soto¹, N J Cely¹, and M L Ayala-Ibarra¹

¹ Grupo de Investigación en Hidrología y Recursos Hídricos, Universidad Francisco de Paula Santander, San José de Cúcuta, Colombia

E-mail: gustavocarrillo@ufps.edu.co

Abstract. In every branch of science, the classification of the object of study shows the degree of understanding reached. Hydrology seeks this sorting system that classifies watersheds globally, a highly complex issue given the degree of heterogeneity of climates, geomorphology, vegetation cover, soils and geology. This project provides ideas on the possibilities of classification of basins in the southern region of the Andean zone in Colombia, from hydrological similarity point of view, evaluated by means of "signatures" that synthesize the hydrological functioning of the basin. Five signatures were considered: Runoff coefficient, base flow index, slope of the flow duration curve, discharge-precipitation elasticity, and hydrograph rising limb density. Geomorphological characteristics and values of hydrological signatures were determined for 25 catchments. Two classification methodologies were implemented: k-means clustering and classification and regression trees. The grouping identified two groups for base flow index, rising limb density and slope of the flow duration curve firms, and three groups for the remaining runoff coefficient and streamflow-precipitation elasticity. No significant correlations were found between hydrological signatures and climatic and geomorphological characteristics, suggesting a degree of complexity within hydrological processes that require the inclusion of other components such as vegetation and soils characteristics. By applying regression trees, the basins were grouped into 4 classes, with the slope of the flow duration curve being the main discriminator and the rising limb density in the second level. The importance of the flow duration curve as an indicator of hydrological processes and the rising limb density as an indicator of the climatic component, the driving force of said processes, is highlighted.

1. Introduction

In a similar way as many other sciences, hydrology is looking for an integrating framework to classify its body of study, and currently the unit of analysis that seems most appropriate to address this process is the river basin or catchment. The catchment is a unit of land that integrates all aspects of the hydrological cycle, bounded by an area that can be studied, quantified and modified [1].

It is usually easy to interpret that, due to unique combinations of climate, topography, vegetation, soils and geology, each basin is unique in the world and therefore it is not possible to generalize [2]. However, from a different perspective, the basin can be considered as a self-organized system, whose shape, drainage network, slopes, soil channels and vegetation are the result of adaptive ecological and geomorphological processes [3]. According to [4], a generalized system of watershed classification:



- Provides an important organizing principle, complementary to the concepts of hydrological cycle and conservation of the mass.
- Help with both modeling and experimentation approaches by highlighting similarities and differences.
- Provides a common communication language.
- Provides better modeling guidelines in poorly understood hydrological system.
- Provides limits and diagnostic indices that can be used for modeling in non-instrumented basins.
- Provides first-order guidelines on the potential effects associated with climate change and land use change.

In the literature, different approaches appear to address the problem of hydrological similarity, such as the Similarity and Classification Indexes presented in [5-7], among others. Other approaches are based on the basin structure, represented by dimensionless numbers such as Peclet number for slopes [8], distribution curves [9] focused with the entries by riparian system and slopes to the drainage network, conceptual and mathematical models.

Researchers have identified the important control exerted by the climate and therefore have developed classifications based on hydro-climatic regions, such as proposals in classical references such as Budyko [10] and L'vovich [11].

Recently the classification schemes have concentrated on considering the functional response [4], which is understood as the operating characteristics within the catchment, evidenced in different hydrological signatures, which can not only be constructed from streamflow time series if not, they can and should include climatic aspects, dynamics of subsurface flows and humidity in the soil, residence times, hydrological composition, vegetation, etc.

This project provides ideas on the possibilities of catchment classification in the southern region of the Andean zone in Colombia, from the point of view of hydrological similarity, evaluated by means of "hydrologic signatures" that synthesize the hydrological functioning of the catchment. Five signatures were considered: Runoff coefficient (RC), base flow index (BFI), slope of the flow duration curve (SFDC), streamflow-precipitation elasticity (EQP), and rising limb density in the hydrograph (RLD). In basins of the Colombian Andean zone, their geomorphological characteristics and values of hydrological signatures were determined. Finally, two classification methodologies were implemented: k-means clustering and classification and regression trees (CART).

2. Methods

Next, the definition of the watersheds selected for the present study is presented, as well as the definition of the hydrological signatures considered, and the classification models implemented.

2.1. Area of study

The study area corresponds to the southern part of the Colombian Andean zone, from where 25 catchments were selected in the departments of Cauca, Huila and Tolima. The selected watersheds have a streamflow gauging station with a historical record of more than 15 years and enough rainfall stations. The delimitation and geomorphological characterization of the catchments was made from a terrain elevation model (TEM) with a spatial resolution of 12.5 m taken from the Vertex data portal of the Alaskan satellite installation of the UAF, and processed in the ArcMap® software, in conjunction with the TauDEM tool developed by the hydrology research group of Professor David Tarboton at Utah State University. Figure 1 presents an example the catchments considered in the department of Cauca. The blue triangles indicate the location of the precipitation stations. Additionally, to the east and northeast of the department of Cauca, the department of Huila and the southern part of the department of Tolima can be seen.

2.2. Hydrological signatures

Five hydrological firms were considered that capture the hydrological response of the basin to the climate that acts on it. The hydrological signatures are:

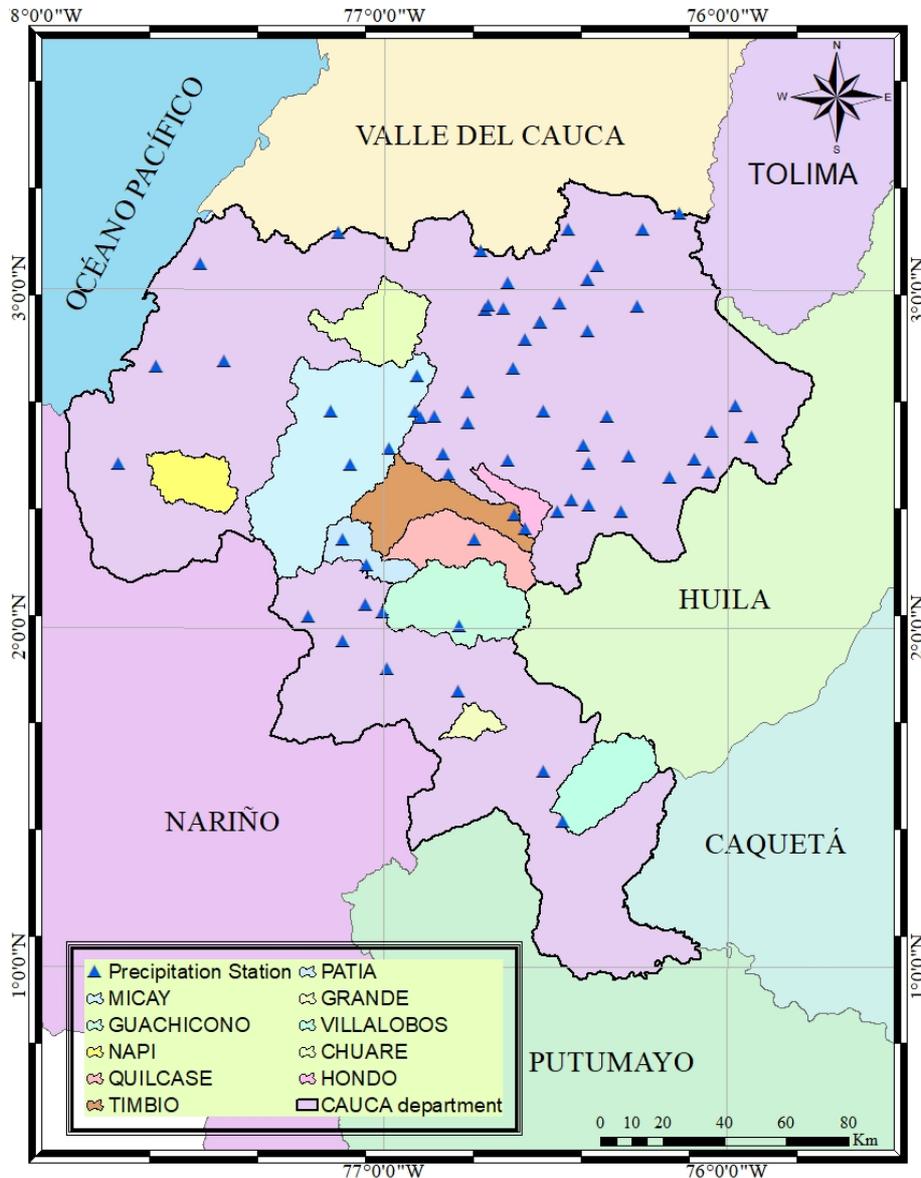


Figure 1. Study catchments and rainfall stations of the department of Cauca (Colombia).

- Runoff coefficient (RC), defined as the dimensionless relationship between average long-term streamflow and average long-term precipitation.
- Base flow index (BFI), a dimensionless relationship between the volume of baseflow divided by the total volume of streamflow. The baseflow was determined by a digital low-pass filter over the time series of mean daily flows.
- Slope of the flow duration curve (SFDC), evaluated between the flows corresponding to exceedance probabilities of 33% and 66%.

- Elasticity of streamflow to precipitation (EQP), estimated as the interannual change of annual flow divided by the interannual change of annual precipitation, which is then normalized by the long-term flow ratio.
- Rising limb density (RLD), defined as the ratio between the number of ascending limbs in the hydrograph and the total amount of time the hydrograph is rising.

2.3 Classification models

Cluster analysis is a technique that allows analyzing and examining data that are not labeled, either by constructing a hierarchical structure or forming groups of groups based on their similarity and a previously specified number, which have meaning in the context of a specific problem. This process includes a series of steps, ranging from preprocessing and development of algorithms, to the validity and evaluation of the solution [12].

The K-Means algorithm is one of the most used algorithms for geometric grouping. Originally proposed by Forgy in 1965 [13] and McQueen in 1967 [14], and often referred to as Lloyd's algorithm, this is a partition algorithm, that is, it divides objects into a pre-specified number of clusters, unattended to a hierarchical structure, it can be applied to problems of "grouping by similarity". It works in an iterative way, optimally dividing the initial set of data into a "K" number of clusters, which is indicated as a parameter. It is based on the minimization of internal distance.

The classification and regression trees (CART) correspond to a general term which combines the generation of groups or classes and the prediction of a numerical value [15]. There are different fundamentally differentiated approaches in how the divisions are made in the different branches of the tree.

3. Results and Discussion

Table 1 presents some geomorphological characteristics of the catchments studied. Catchments areas vary across a wide range, with values between 26 km² and 7737 km², with maximum elevations around 5200 m.a.s.l. and high values for catchment mean slopes with average values around 40%. These geomorphological values are typical of the Colombian Andean zone. Following the method of K-means clustering for each of the hydrological signatures, the following results were obtained:

- According to RC, three groups were identified, for values lower than 0.50, between 0.50 and 0.70, and greater than 0.70. No correlations were found between the groups and their geomorphological characteristics.
- According to BFI, two groups were identified, 5 catchments with BFI less than 0.72 associated with low average slopes, and the remaining basins with values greater than this limit.
- According to SFDC, two groups were identified, the first with values between 0.98 and 1.5, and the second group with values greater than 1.5 to 2.94. As for the RC, no correlations were found between the groups and their geomorphological characteristics.
- According to EQP, 3 groups were identified with values lower than 0.40, between 0.40 and 1.2, and higher than 1.2, reaching 1.61. There is a slight inverse correlation between EQP and the slope of the basin.
- Finally, according to RLD, 2 groups were identified, with values between 1.50 and 1.60 for the first group, and values between 1.60 and 1.80 for the second group. No correlations were found between the groups and their geomorphological characteristics.

Considering the signatures base flow index (BFI), rising limb density in the hydrograph (RLD) and slope of the flow duration curve (SFDC) the basins were classified into 2 groups, high values (BFI between 0.73 and 0.87) and low (BFI between 0.61 and 0.72), and for the firms Runoff coefficient (RC) and Flow elasticity (EQP) were classified into 3 groups, high (EQP between 1.49 and 1.61),

means (EQP between 0.67 and 1.12) and low (EQP between 0.02 and 0.40). These values suggest a first guide in the establishment of hydrological similarity between basins.

Table 1. Catchments geomorphological characteristics.

Catchment	Area (km ²)	Perimete (km)	Maximum elevation (m a.s.l.)	Minimum elevation (m a.s.l.)	Mean slope (%)	Mean Elevation (m a.s.l.)	Drainag order
Grande	130	68.3	3641	2293	28.82	3029	4
Villalobos	643	126.2	3276	895	38.74	2002	4
Patia	1700	257.8	4436	623	36.53	1633	4
Quilcase	623	163.1	4436	654	34.17	1643	3
Timbio	767	205.8	3698	655	37.24	1705	3
Guachicono	960	168.7	4434	735	42.53	2204	4
Napi	415	112.9	3894	33	34.53	678	4
Micay	2378	287.6	3813	116	55.09	1500	5
Chuare	601	145.8	3373	97	52.39	1007	5
Hondo	198	94.5	3331	1603	25.89	2192	3
Cabrera	1663	250.4	4040	670	33.58	2130	3
Guarapas	248	105.9	2910	1283	32.19	1859	3
Paez	4839	429.5	5415	819	41.67	2531	4
la Plata	1218	206.1	4673	1157	33.27	2423	5
Suaza	994	202.9	2917	922	38.15	1632	3
Yaguara	669	142.2	3658	609	39.52	1423	4
Ceibas	104	61.6	3216	1368	54.06	2303	5
Cuinde	26	27.0	1825	717	27.10	1159	4
Negro	442	137.0	3080	411	23.33	1557	5
Ata	1382	230.7	4565	763	48.91	2644	3
Saldaña	7737	548.7	4626	338	45.82	2126	4
Combeima	166	65.3	5244	1466	59.57	2922	5
Lagunilla	175	76.9	5241	1213	42.93	2944	3
Guali	461	169.8	5279	519	47.77	2411	4
San Vicente	106	49.4	5244	1765	58.57	3171	4

In order to seek an understanding of the groups created, the geomorphological characteristics of the watersheds within each group were analyzed, in order to show if these characteristics can explain the already classified groups. However, the results showed no significant trends. Moderate correlations are evidenced between BFI and EQP with the average slope of the basin in a directly proportional and inversely proportional way, respectively. It is possible that this relationship is due to similarities between the geological and soil characteristics present in the catchments, which are reflected in an index variable such as the slope of the basin.

Figure 2 presents the result of applying the classification tree algorithm for the 25 catchments considering the values of the 5 hydrological signatures considered as a criterion. The result groups the catchments into 4 classes, identifying the slope of the flow duration curve (SFDC) as the first classification criterion, with a threshold value of 2.3. The rising limb density in the hydrograph (RLD) is identified as the second classification criterion.

Classes 1 and 2 correspond to catchments with relatively low variability of flows, where Class 1 attenuates the variability of the precipitation signal, with respect to Class 2. Classes 3 and 4 correspond to catchments with relative high variability of flows, where again Class 3 decreases to a greater degree the variability of the precipitation signal, with respect to Class 4.

The hydrological signature SFDC is identified as a good discriminant of the hydrological processes within the catchment, and RLD signature indicates the importance of an adequate characterization of the forcing of the hydrological cycle, via precipitation.

To date, no scientific production was found that covers Colombia in terms of proposals for catchments classification. In contrast, this is an active topic in research conducted in North America and Europe. For example, in [16] an empirical classification study was carried out for 280 basins in the eastern United States, to understand hydrological similarity based on 6 hydrographic signatures. Recently, in [17] an extensive study is presented to improve the understanding of physical controls in spatial patterns of hydrological signatures, where 16 hydrological signatures and 3 descriptors were considered on 35215 catchments analyzed. Among the many conclusions of these two studies, they agree that climate exerts the primary control to differentiate or classify the catchments and, in a second degree of importance, the modification of the climatic signal caused by the characteristics of each basin appears. It is striking that the present study finds that, unlike studies in North America and Europe, it is the characteristics of the basins that exercise primary control (e.g. SFDC) and in the second line the climatic characteristics appear (e.g. RLD). This could be explained since the current area of study is much smaller than that of other international studies, therefore the catchments analyzed would be subject to very similar climates

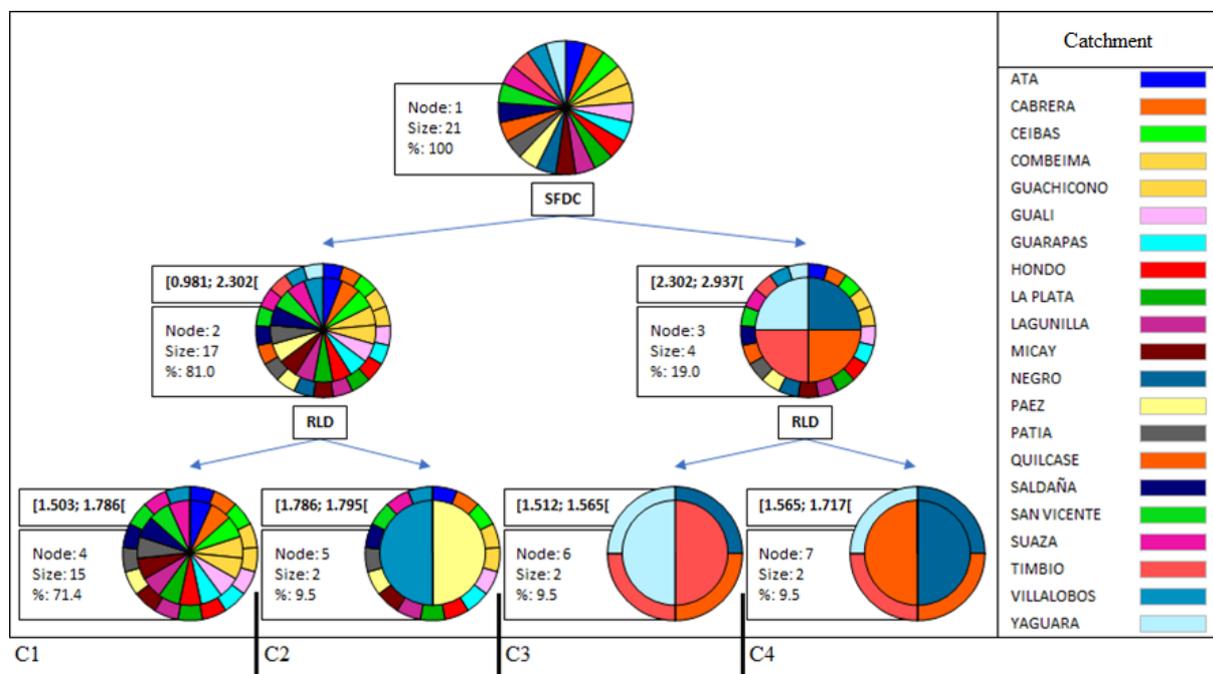


Figure 2. Classification tree considering the 5 hydrological signatures.

4. Conclusions

A study of basin hydrological similarity was developed in the southern area of the Colombian Andean region, based on the analysis of hydrological signatures, where it was identified that the slope of the flow duration curve exerts a primary classification control, and as a control secondary the rising limb density was identified. This suggests that it is the physiographic characteristics of the basins that exercise a criterion of discretization more important than the climate, a result that contrasts with studies carried out in North America and Europe, where it is the climatic characteristics that prevail. This difference is possibly explained by the size of the area considered in the different studies.

The results seem to suggest that geomorphological and climatological characteristics, by themselves, do not adequately explain the different groupings by hydrological signature similarity, then it may be necessary to recombine these characteristics, and very likely include other characteristics such as vegetation, soil type, geology, etc.

It is important to recognize that, although the results found in this study cannot be extrapolated to other climatic areas in Colombia, this is the first study on this subject, which invites the scientific

community to continue with this type of analysis, by extending it to other regions and to be able to advance in the understanding of tropical hydrology in contrast to other regions of the world widely studied, but at higher latitudes with a clearly different climatic input.

The results also identify the flow duration curve as a relevant hydrological signature, which should be an important criterion in hydrological similarity issues, as well as in processes of identification (calibration) of hydrological models, and the progress in the behavior prediction of ungauged catchments, which turn out to be the majority in Latin American countries.

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