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REGIONALIZATION OF FLOW DURATION CURVES IN THE STATE OF ANTIOQUIA, COLOMBIA

Santiago Gallego Arias[1]
Luis Fernando Carvajal Serna[2]

ABSTRACT

Water resource design and projects need sufficient information and data processes to ensure proposed hydraulic structures are successful. Many hydrological studies have no observed data for discharges in the basins, and one of the most commonly used concepts for previous hydrological studies is the flow duration curve. This work shows a new approach to estimate the flow duration curve in basins for which there is no information. The proposal presents a calibrated equation for each of the six regions in the state of Antioquia, in the northwest of Colombia. Veering from the traditional approach, it includes the non-exceedance probability. The statistical analysis conducted shows a fitting error of less than 13% for all regions in Antioquia except Urabá, which has an error of 44%.

KEYWORDS: Discharges, Duration Curve, Discharge Regionalization, Basins with no Gauge Information, Antioquia.

REGIONALIZACIÓN DE CURVAS DE DURACIÓN DE CAUDALES EN EL DEPARTAMENTO DE ANTIOQUIA-COLOMBIA

RESUMEN

Los diseños y aprovechamientos en recursos hidráulicos requieren de la información y procesamiento de datos necesario para el éxito de las obras propuestas. Muchas veces los registros de caudal no están disponibles en la cuenca hidrográfica de estudio y uno de los conceptos más usados es la curva de duración de caudales. Este trabajo propone un nuevo acercamiento a la regionalización de la curva de duración de caudales en cuencas sin información. El enfoque presenta una ecuación para cada una de las 6 regiones en que se dividió el departamento de Antioquia, en la parte noroeste de Colombia. La propuesta tiene como variable adicional al enfoque tradicional, la inclusión de la probabilidad de no excedencia. El análisis estadístico realizado muestra que el error de ajuste es menor del 13% para todas las regiones de Antioquia con excepción de la región de Urabá, que es del 44%.

PALABRAS CLAVE: Caudales, curva de duración, regionalización de caudales, cuencas hidrográficas con información escasa, Antioquia.

[1] Ingeniero Civil. Universidad Nacional de Colombia
[2] Ingeniero Civil. Maestría en Recursos Hidráulicos. Universidad Nacional de Colombia

Author's Mailing Address: Carvajal Serna L.F. (Luis Fernando): Facultad de Minas, Cl. 80 #65 - 223, Medellín, Antioquia, Colombia. Tel.: (574) 425 51 09
Email: lfcarvaj@unal.edu.co

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REGIONALIZAÇÃO DAS CURVAS DE PERMANÊNCIA DE VAZÕES NO DEPARTAMENTO DE ANTIOQUIA, - COLÔMBIA

RESUMO

Os desenhos e aproveitamentos em recursos hídricos precisam de informações e processamento de dados necessário para o sucesso das obras propostas. Muitas vezes, os registros de vazões não estão disponíveis na bacia hidrográfica de estudo e um dos conceitos mais utilizados é a curva de duração de fluxo. Este trabalho propõe uma nova aproximação à regionalização da curva de duração de volumes em bacias sem informação. O enfoque apresenta uma equação para cada uma das 6 regiões em que se dividiu o departamento de Antioquia, na parte noroeste da Colômbia. A proposta tem como variável adicional ao enfoque tradicional, a inclusão da probabilidade de não excedência. O análise estatísticO realizado mostra que o erro de ajuste é menor de 13% para todas as regiões de Antioquia com exceção da região de Urabá, que é de 44%.

PALAVRAS-CHAVE: Fluxo, a curva de permanência, racionalização de fluxos, bacias hidrográficas com informações limitadas, Antioquia.

1. INTRODUCTION

Colombia is a country characterized by its waterways and water sources. For the proper management and planning of these resources, it is very important to monitor the flow rate. The flow records for a water basin are basic information for hydrological studies. Depending on the objective of the study, this includes annual and monthly mean flow rates for analysis of water supply and demand or long-term energy analysis, as well as maximum and minimum flow rates for the design and operation of hydraulic works associated with a return period (Ven Te Chow et al., 1994).

The quality of the hydrological information is extremely important. The most reliable is that which comes from direct data acquisition, in the case of flow rates by using limnigraphic and limnimetric stations. This type of information source requires field collection, processing, and quality control. Apart from reviewing the measurements, data processing and calibration curves, a homogeneity analysis is also done. In this case parametric and non-parametric tests are used in the mean, variance, and trend of the series (Machiwal and Kumar, 2012).

Flow rate monitoring requires measurement networks which would ideally have the greatest coverage in the study area. The installation of measurement stations has the following criteria: operation and maintenance costs and accessibility.

On the other hand, the study of water use projects in which flow rate information is not available is common in Colombia. This situation adds uncertainty to the hydrological studies necessary for project feasibility: aqueducts, flood control, irrigation, hydraulic power stations, etc. To solve this problem, surface hydrology allows for the reconstruction of flow rate information in water basins where there are no flow rate records. This line of work is known as hydrology with scarce data. The main idea is to transpose, by means of generally statistical methods, the characteristics of the basin with information to the basin that is lacking information, bearing coherence or hydrological criterion in mind. Hydrological coherence is represented in the hydrological regime, that is, both basins must have similar hydrological behavior, precipitation, winds, topographic conditions and similar soil uses, which implies that the response of the surface runoff or flow is similar(Guarín and López, 1986; Gómez Cano et al.,1990;Bolaños, 1995; Vélez, poveda and Mesa, 2000).

One of the most useful concepts in hydrology is the flow duration curve (FDC). This curve is used for studies on water availability, hydraulic design, swells, ecological flows and the feasibility of hydraulic projects. The FDC requires constant reviewregarding both new estimation approaches and updating the equations as new records become available.

An alternative that addresses this problem utilizes the FDC as an exponential function that depends on the probability of non-exceedance, and two curves are adjusted, one for a probability less than 50% and another for a probability greater than 50%(Vélez, Smith, Pérez, Franco, & Bolaños, 1995). At the national level, the most recent proposal is presented by the *Atlas potencial hidroenergético de Colombia* (in English, "Atlas of Hydraulic Potential of Colombia"), in which the FDC is estimated through regionalization by adjusting a linear regression between the flow rate and the coefficient of variation (CV) for a set of 17 subregions (UPME-UPJ, 2015).

This project aims to propose a new method for estimating the FDC in streams or rivers in the Department of Antioquia. It presents the regionalization equations of the FDC for different regions of the department, which were defined by taking the hydrological regime into account for each area.

The article consists of a description of the information and the method for FDC estimation with scarce data, statistical fit and regionalization equations, analysis of results and, finally, conclusions and bibliographical references.

2. HYDROLOGICAL AND TOPOGRAPHICAL INFORMATION

For studies aimed at establishing relationships between hydrological variables, the analysis of the spatial variability of precipitation is very important, especially for the determination of the average flow of the basin. Methods such as long-term hydrological balance show consistent results in this respect (Vélez, Poveda & Mesa, 2000).

In Colombia, precipitation variability is mainly defined by: (1) tropical conditions under the influence of trade winds and oscillation of the Intertropical Convergence Zone; (2) its surroundings, the Pacific and Atlantic Oceans being sources of humidity; (3) topography, including the presence of the Andes mountain range, which causes significant climatic differences between the inter-Andean valleys; (4) circulation of the Amazon Basin, and (5) variability of surface hydrology processes such as the contrasts in soil moisture and evapotranspiration, heavily influenced by vegetation, soil type and local wind circulation (Mesa, Poveda & Carvajal, 1998; Poveda, 2004).

Another important aspect is variation of precipitation with altitude. In tropical areas such as Colombia, the so-called optimal pluviography is well known and corresponds to an elevation at which the precipitation is at its maximum between the base level and the top of the mountain ranges. Precipitation is also affected by the location on each of the three Andean branches. As for the amount of precipitation in Colombia, the rainiest areas are in the western slopes of the western mountain range and the eastern slope of the eastern mountain range(Vélez et al., 2000). Explanation is given in the form of the circulations generated in the inter-Andean valleys and in the interaction between the predominant trade winds of the east and the winds that penetrate through the west, from the Pacific Ocean into the interior of the country.

Three important river valleys can be identified in the department of Antioquia: the Atrato river valley in the west; the narrow Cauca river valley in the center; and the great valley of the Magdalena river in the east. Alternating with these valleys are the *Cordillera Occidental* (West Andes) between the Atrato river depression and the Cauca river valley, and the *Cordillera Central* (Central Andes) between the Cauca river valley and the Magdalena river valley. The West Andes is formed mainly by parallel and transverse branches to the main axis, while the Central Andes range is dominated by two large plateaus: Santa Rosa de Osos to the north and Rionegro to the south, separated by the canyon of the Porce river (Bolaños, 1995). It is also shaped by the lower Cauca, where the central mountain range ends. Finally, there is the *Urabá Antioqueño* (Antioquian Urabá) area, which connects with the foothills of the western mountain range and provides an outlet for the department to the Caribbean Sea.

Due to the high altitude of the western range, a large part of the rain coming from the department of Chocó falls on the western slope, leaving the eastern slope with less precipitation. The difference in coloration of the vegetation between the more arid eastern slope and the more humid western slope of the central range is a clear indicator of this process, since both areas are marginally separated by the Cauca river.

The information required for this work comes from three sources: daily mean precipitation, the digital terrain elevation model (DTM) and daily mean flow records.

The DTM used is obtained from the SRTM (Shuttle Radar Topography Mission). This DTM has a high degree of post-processing when contrasted with real values, and also relies on NASA's ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) mission model for the correction of spurious data, see **Figure 1**.

Figure 1. Digital terrain elevation model. Antioquia department

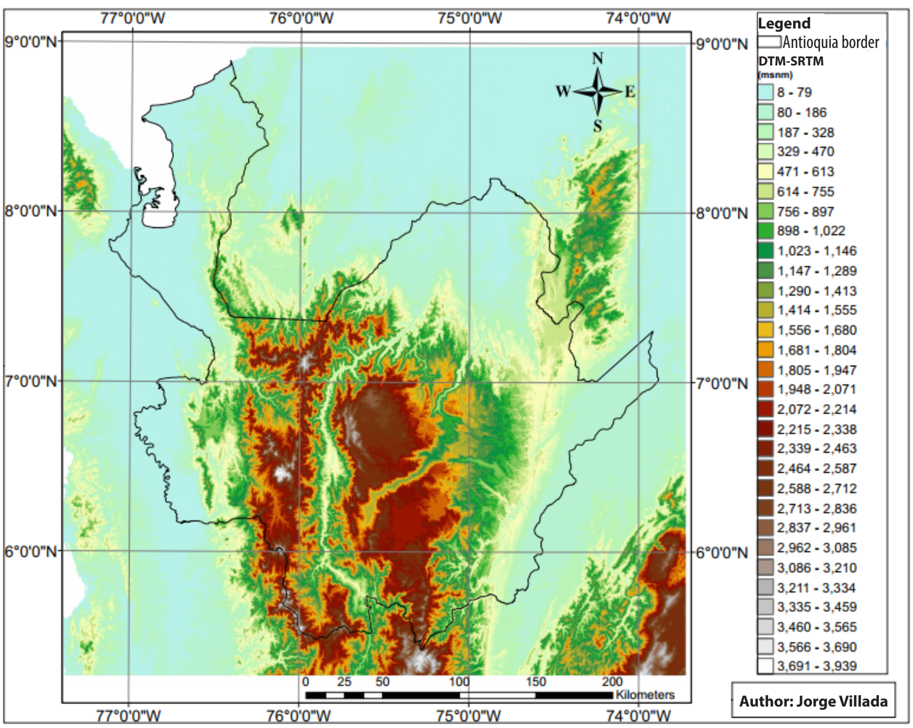


Figure 2. Department of Antioquia hydrological zones and distribution of flow stations

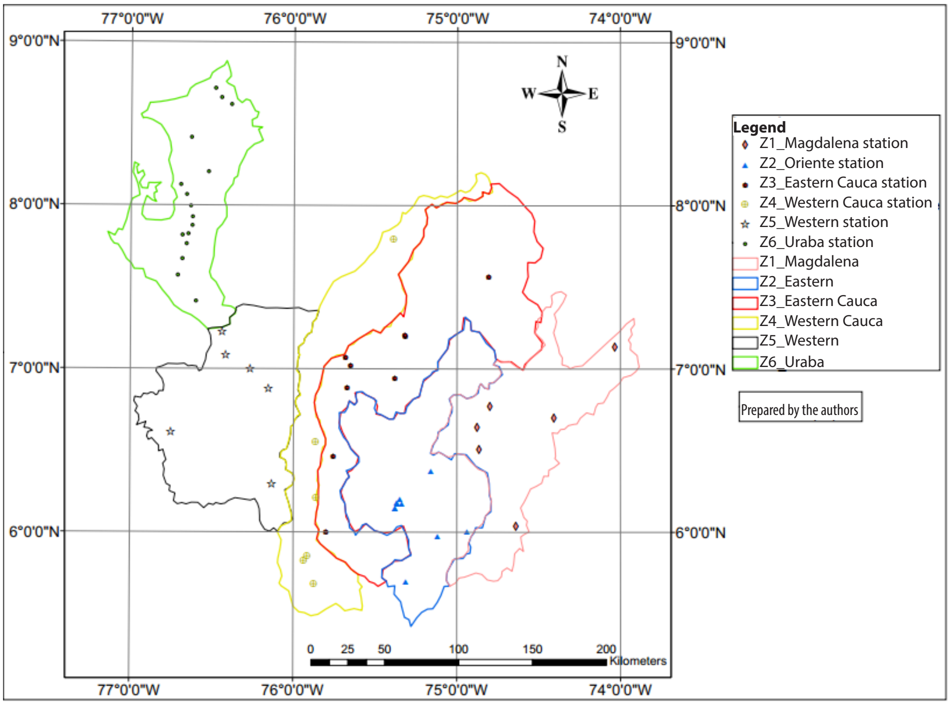
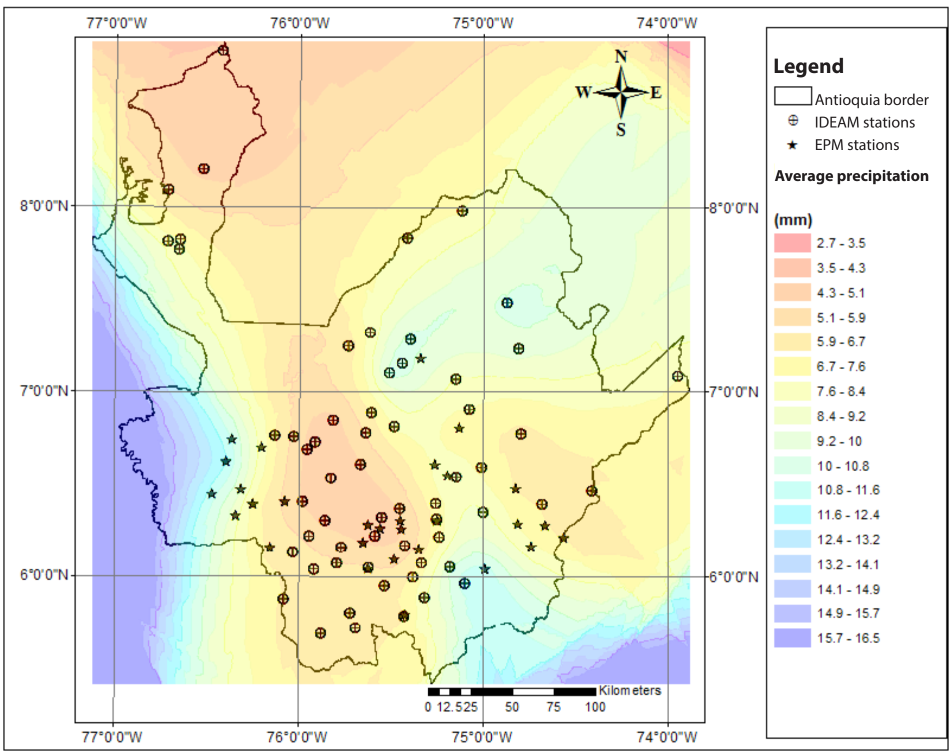


Figure 3. Map of average daily precipitation and location of IDEAM and EPM precipitation stations



Furthermore, for this study the department of Antioquia has been subdivided into 6 zones. Information on daily average flows was provided by the Institute for Environmental Studies, (*IDEAM*, in Spanish). An attempt was made to request all possible information from this entity, obtaining the average daily flow from a total of 79 stations that operate throughout the department of Antioquia. This information was submitted to a selection process, taking into account criteria such as the following: the net number of records must exceed 10 years; the records of the Atrato, Cauca and Magdalena rivers were purged from the analysis since it was believed that their hydrological behavior was dependent on factors external to those that dominate the Antioquian area.

Figure 2 shows the subdivision of the department into the hydrological zones together with the distribution of the flow stations selected in the end.

The monthly precipitation information includes a total of 61 stations within the Antioquia department operated by IDEAM. To complement those areas that were lacking precipitation data, the information presented in the work of Smith and Vélez (1998) was used. This information corresponds to 29 stations operated by Empresas Públicas de Medellín (EPM).

The average daily precipitation map was obtained from the Kriging technique with external drift, in this case, the DTM dimensions, supported by ArcMap 10 software. **Figure 3** shows the location of precipitation stations in Antioquia and the precipitation map resulting from Kriging interpolation.

3. ESTIMATION OF REGIONALIZED FLOW DIMENSION CURVES

The FDC is a tool used to indicate the distribution of the occurrence of flow rates over time (Guarín and López, 1986). For its creation, the recorded flow values are ordered from highest to lowest, and the probability of exceedance (Weibull empirical probability function) is assigned to each flow value. Then, the flow data is plotted on the y-axis and the respective probability values are plotted on the x-axis.

$$FE\,(x) = \frac{m}{N+1} \tag{1}$$

Where:

$FE\,(x)$ = probability of exceedance of the value “x”.

m= position in the column arranged from greatest to least of the value “x”.

N= total number of data.

For this paper, a regionalization of flow duration curves was performed based on the hydrological homogeneity of an area and taking the topography and rainfall regime into account. Following the procedure of regionalization of average flow characteristics presented in Smith and Vélez (1997), the procedure that was developed is as follows:

a) Flow stations with an equivalent net recording greater than ten years were selected. The FDC is created for each of these sets. A minimum length of 10 years is due to having at least one El Niño-Southern Oscillation phenomenon and to discard a larger number of flow stations.

b) Areas that may have a similar hydrological behavior are defined; initially the division by Jaramillo and Chávez(2000) was considered. The division also considered the seasonal distribution of rainfall, in addition to total precipitation and geographical location.

c) The average daily flows of each station are plotted for each zone compared to the flows of the different percentiles or probabilities of non-exceedance of the FDC.

d) For each area, the fitting was considered with the following equation:

$$Q_p = \frac{AQ_m + B}{D \quad \frac{P_q}{C}} \qquad (2)$$

Wherein:

Q_m: is the average daily flow of the basin in m^3/s.

A, B, C and *D* are parameters.

P_q: is the probability of non-exceedance in the FDC as a percentage.

Q_p: is the flow rate value of probability of non-exceedance in m^3/s.

Equation 2 allows for the use of a single expression for each area with only having the mean flow rate and replacing P_q with the value of the percentage of the flow time to be calculated or probability of non-exceedance. **Equation 2** is suggested by the relationship observed when plotting the mean daily flow values versus the flow rate values of different non-exceedance probabilities, Q_m *vs* Q_p. **Figure 4** shows the relationship for area 3 of the flow rates with a non-exceedance probability of 30, 50 and 70% for each basin.

As observed in **Equation 2**, it is necessary to know the mean daily flow of the basin, which can be estimated by different methodologies, such as yield, which is based on a proportionality of areas(Gómez Cano et al., 1990), or the water balance equation (Vélez et al., 2000). The long-term water balance equation is expressed in the following manner:

$$Q_m = (P - E)\,A \qquad (3)$$

Wherein:

Q_m : is the average annual flow in m^3/s.

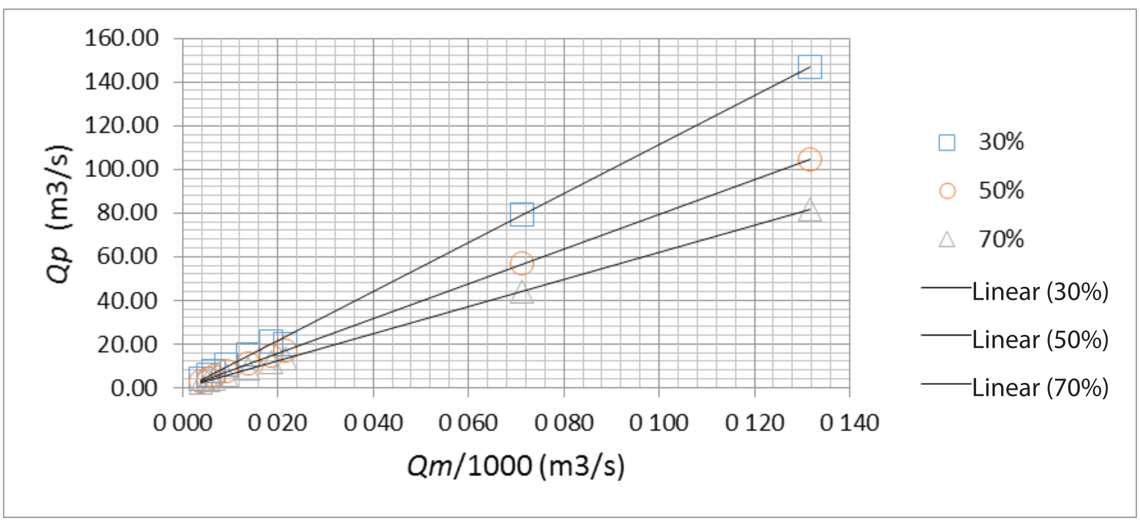
P : is the average annual rainfall in mm/day.

E : is the average annual surface evapotranspiration in mm/day. To estimate evapotranspiration the Cenicafé equation is used, combined with the Budyko equation (Vélez et al., 2000).

A : is the area of the basin in m^2.

As an alternative to the calculation of the average daily flow, a regionalization flow rate equation is proposed according to geomorphological parameters. The procedure is as follows:

Figure 4. Qm vs. Qp for different non-exceedance probabilities in area 3, tributaries of the eastern slope of the Cauca river basin, Antioquia Department



a) The geomorphological parameters are measured for the basins defined by the gauging station as the area, perimeter, slope of the main channel, average slope of the basin, in addition to the multi-annual daily average precipitation.

b) With the geomorphological and climatic variables measured, the expression 4 is fitted to establish the average flow, Q_m, of the basins:

$$Q_m = KA^{\alpha}\, Sppl^{\theta}\, Sc^{\delta}\, Kc^{\mu}\, Pm^{\beta} \qquad (4)$$

Where:

$K, \alpha, \theta, \delta, \mu$ and β are parameters found in the regression.

A is the basin area in km^2.

Sppl is the average slope of the main channel in %.

Sc is the average slope of the basin in %.

Pm is the average daily rainfall in the basin in mm/day.

Qm is the average daily flow of the basin in m^3/s.

Kc is the Gravelius coefficient, the relationship between the perimeter of the basin and the perimeter of a circle of the same area as the basin:

$$Kc = 0.28\,\frac{Per}{\sqrt{A}} \qquad (5)$$

Where:

Per is the perimeter of the basin in km.

A is the area of the basin in km^2.

This method assumes that the area for which the mean daily flow rate is to be determined has similar geomorphological and climatological characteristics according to the regions defined in the department of Antioquia.

For the estimation of the fitting error of the duration curves, the average of the percentage relative error in absolute value was used, defined as:

$$E\bar{r}r\,\% = \frac{1}{N}\sum_{i=1}^{N}\frac{|O_i - E_i|}{O_i} \times 100 \qquad (6)$$

Where:

E : is the value of the estimated flow in m^3/s.

O : is the value of the observed flow in m^3/s.

N : is the amount of data.

$E\bar{r}r$ %: is the average percentage relative error.

4. RESULTS

The equations for the regionalized flow duration curve found for each of the zones are presented below. These curves have been fitted for the range of 10% to 90% of flow duration or non-exceedance probability.

Area 1: Magdalena area

$$Q\,\% = \frac{27.048Qm + 5.092}{10.47 + \frac{Pq}{2.064}},\ E\bar{r}r\,\% = 13.15\,\% \qquad (7)$$

Area 2: Eastern area

$$Q\,\% = \frac{26.7Qm}{10.494 + \frac{Pq}{2.07}},\ E\bar{r}r\,\% = 10.85\,\% \qquad (8)$$

Area 3: Eastern Cauca area

$$Q\,\% = \frac{28.217Qm}{10.031 + \frac{Pq}{1.97}},\ E\bar{r}r\,\% = 9.68\,\% \qquad (9)$$

Area 4: Western Cauca area

$$Q\,\% = \frac{27.621Qm + 1.88}{10.345 + \frac{Pq}{2}},\ E\bar{r}r\,\% = 12.84\,\% \qquad (10)$$

Area 5: Western area

$$Q\,\% = \frac{28.424Qm}{10{,}452 + \frac{Pq}{2.143}},\ E\bar{r}r\,\% = 8.16\,\% \qquad (11)$$

Area 6: Urabá area

$$Q\,\% = \frac{3.834Qm}{},\ E\bar{r}r\,\% = 44.05\,\% \qquad (12)$$

$$-0.8 + \frac{Pq}{3.97}$$

The other aspect to be calculated is the average daily flow rate, which can be determined with **Equations 13** to **18**. It should be clarified that the typical error in some areas (Eastern Magdalena, Western and Southwestern Cauca) is not calculated because 5 types of variables were used in the regression (*A, Sppl, Sc, Kc* and *Pm*), and in those places only a total of 5 stations were available, so in theory the error is zero.

Area 1: Magdalena area

$$Q_m = 0.4763A^{1.0047} S_{ppl}{}^{1.4579} S_c{}^{-3.8923} K_C{}^{-2.0933} P_m{}^{5.5282}\text{, error= ---\%} \quad (13)$$

Area 2: Eastern area

$$Q_m = 0.00575A^{1.208} S_{ppl}{}^{0,4109} S_c{}^{-0.696} K_C{}^{1.441} P_m{}^{1.4087}\text{, error= 29\%} \quad (14)$$

Area 3: Eastern Cauca area

$$Q_m = 0.00027A^{0.9815} S_{ppl}{}^{0.1934} S_c{}^{0.2573} K_C{}^{1.2561} P_m{}^{1.6578}\text{, error= 14.8\%} \quad (15)$$

Area 4:Western Cauca slope

$$Q_m = 8.3 \times 10^{-12} A^{1.4532} S_{ppl}{}^{3.1542} S_c{}^{1.5184} K_C{}^{8.8151} P_m{}^{2.6258}\text{, error= ---\%} \quad (16)$$

Area 5:Western area

$$Q_m = 40.0395A^{0.9292} S_{ppl}{}^{-0.7731} S_c{}^{-1.0114} K_C{}^{1.764} P_m{}^{-1.1572}\text{, error= ---\%} \quad (17)$$

Area 6: Urabá area

$$Q_m = 0.0165A^{1.3284} S_{ppl}{}^{1.0472} S_c{}^{-1.7516} K_C{}^{-1.5558} P_m{}^{2.5213}\text{, error= 28.7\%} \quad (18)$$

5. CONCLUSIONS

A number of useful equations have been reached for assistance in the preliminary evaluation of hydroelectric projects in the department of Antioquia. They will be most useful in areas with no flow information.

Area 6, the Urabá region, presents the highest error rates; among other fitting difficulties, it is necessary to carry out a validity verification process on the information.

In hydrology, regionalization analyses allow for the estimation of the hydrological variable of interest in areas without information, which leads to a gain in spatiality in the results and analysis. But, due to high variability, the uncertainty in these methods in basins in intertropical zones that are not very far each other must be considered, especially convective processes in basins.

Future studies should take into account a larger network of measurement, considering the information of other entities' flows. Additional information allows for an improvement in the estimation of the parameters of the equations.

The results obtained are at the pre-feasibility level and do not negate the requirement to carry out detailed studies for each project and make the most appropriate decisions for it.

The regionalization equations presented in this article show an adequate fit for a range of probability of exceedance between 10% and 90%. Outside of this range it was found that, for the estimation of extreme values, the calculated error increases strongly, indicating large hydrological differences.

REFERENCES

Bolaños Arias, H. D. Regionalización de caudales mínimos en el departamento de Antioquia. Trabajo de Grado, Universidad Nacional de Colombia, Sede Medellín, 1995. 150 p.

Gómez Cano, G. I., Piedrahita Moreno, J. J., Rojas Monsalve, J. J. y Sanz Henao, J. A. Metodología para el inventario de centrales hidroeléctricas de mediana capacidad entre 10 y 100 MW y su aplicación a una cuenca específica. Trabajo de Grado, Universidad Nacional de Colombia. 1990. 244 p.

Guarín Flórez, N. de J., y López Ospina, G. V. Regionalización del comportamiento esperado de estructuras hidráulicas de derivación operadas a filo de agua. Trabajo de Grado, Universidad Nacional de Colombia, 1986. 189 p.

Jaramillo-Robledo, Á., & Chaves-Córdoba, B. (2000). Distribución de la precipitación en Colombia analizada mediante conglomeración estadística. Cenicafé, 51(2), pp. 102–113.

Machiwal, D. y Kumar, M. Hydrological Time Series Analysis-Theory and Practice. Ed. Springer, 2012. 316 p.

Poveda, Germán; Mesa, Oscar y Carvajal, Luis F. Introducción al clima de Colombia. Editorial Universidad Nacional de Colombia, 1998. 390 p.

Poveda, Germán (2004). The hydro-climatology of Colombia: a synthesis from inter-decadal to diurnal timescales (in Spanish). Rev Academia Colombiana de Ciencias, 28(107), pp. 201-222.

Smith Quintero, Ricardo y Vélez Otálvaro, María V. Hidrología de Antioquia. Universidad Nacional de Colombia y Secretaría de Obras Públicas de Antioquia, Medellín, 1997, 163 p.

UPME-PPUJ. Atlas potencial hidroenergético de Colombia. 2015. 160 p.

Vélez, María V., Smith, Ricardo, Pérez, Carlos A., Franco, Carlos Jaime y Bolaños, Hernán (1995). Aplicación de algunas técnicas al diseño hidrológico con información escasa. Revista Avances en Recursos Hidráulicos, Posgrado en Aprovechamiento de Recursos Hidráulicos, núm. 3, pp. 35-54.

Ven Te, Chow, Maidment, David y Mays, Larry. Hidrología Aplicada. Ed. MacGraw-Hill, 1994, 582 p.

Vélez, Jaime I., Poveda, Germán y Mesa, Oscar. Balances hidrológicos de Colombia. Medellín: Universidad Nacional de Colombia, 2000. 150 p.

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