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Articles

Non-stationary modeling of the magnitude and frequency of floods in Alto Cauca through climatic and reservoir operation indexes

Modelación no estacionaria de la magnitud y frecuencia de las crecidas en el Alto Cauca mediante índices climáticos y de operación de embalse

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Abstract

In this study, changes in the frequency and magnitude of annual floods in the Cauca River (Southwest Colombia) are modeled using a non-stationary framework by means of the Generalized Additive Models of Localization, Scale and Shape. Non-stationary flood frequency analysis incorporates two climatic indices and an anthropic index that allows us to assume that changes in the water reservoir and the percentage of regulated tributary area are factors which disturb the capacity of the dam to withhold the flood. The results highlight the role of the El Niño Southern Oscillation (ENSO) phenomenon and the proposed Reservoir Index, as significant covariates in the parameters of the selected distributions. The dependence of model parameters on covariates improves the model's capacity for representing temporal variability of the flood regime. Non-stationary models indicate significant differences in the flow associated with a specific return period, and in the failure risk of flow design, depending on the working life, in contrast to classical stationary models. The main conclusion is that since 1986 in the gauging station Juanchito, flooding has shown a gradual increase in magnitude, which is unambiguously associated with the cold phase of the ENSO phenomenon. Therefore, the non-stationary models provide valuable information on the reservoir, its regulation strategy for high flow, and for flood risk management in the Cauca river basin.

Keywords: Floods frequency analysis, non-stationary, El Niño South Oscillation Phenomenon, Colombia, anthropogenic interference.

Resumen

A través de los modelos aditivos generalizados de localización, escala y forma se estudian los cambios en la frecuencia y magnitud de las crecidas anuales en el río Cauca, localizado en el suroccidente de Colombia. El análisis de frecuencias de crecidas no estacionario incorpora dos índices macroclimáticos y un índice antrópico, que permite asumir los cambios en el almacenamiento de agua en el embalse y el porcentaje de área tributaria regulada, como factores que inciden en la capacidad de la represa para laminar las crecidas. Los resultados muestran que forzamientos que dependen del Índice Multivariado del Fenómeno El Niño Oscilación del Sur (ENSO, por sus siglas en inglés) y del índice de embalse propuesto, cuando son aplicados a los parámetros de la función de distribución, mejoran la calidad de ajuste y la descripción de la variabilidad temporal de la serie de tiempo de crecidas. Frente al análisis convencional, los modelos no estacionarios indican diferencias significativas en los caudales asociados con cierto periodo de retorno y en el riesgo de fallo de un caudal de diseño en función de la vida útil. La principal conclusión es que desde 1986, en la estación de aforo Juanchito, los caudales exhiben un incremento en magnitud que está asociada inequívocamente con eventos de la fase fría del fenómeno ENSO. Por lo tanto, los modelos no estacionarios proveen información de interés para el embalse, su estrategia de regulación de caudales altos y en la gestión del riesgo de inundaciones.

Palabras clave: análisis de frecuencias de crecidas, no estacionariedad, fenómeno ENSO, Colombia, alteración antrópica.

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Introduction

The climatic variability associated with ENSO is of profound environmental and socioeconomic impact in Colombia. The cold phase of ENSO generates emergencies due to flooding and landslides, potentially affecting more than 500,000 people with a 2- to 4-year frequency. During the period 1950-2018, 177 natural disasters were reported in the country, with 45% of cases corresponding to floods (EM-DAT, 2018). Furthermore, in relation to Latin America, Colombia has the highest rate of recurrent emergencies caused by natural phenomena (more than 600 reports per year); due not only to natural environmental conditions, but to the fact that 84.7% of the population are located in areas exposed to two or more natural hazards (Banco Mundial, 2014).

Flood Frequency Analysis (FFC) is the statistical model most frequently used to estimate the flooding flow rate and / or its frequency of occurrence, in order to determine the size of hydraulic structures and manage water resources in a basin. The analysis makes inferences about a hydrological variable, assuming the hypothesis that the observations are independent and identically distributed (i.i.d. hypothesis); therefore, there are no systematic changes in the mean or variance that determine the appearance of trends during the observation period, nor in the extrapolations made on said data. However, there is evidence of the effects of global environmental changes and climate variability in relation to the alteration of the behavior of hydrological variables in both space and time, which explains why statistical methodologies that address non-stationary FFC have been under development for more than a decade.

Previous studies on the effects of climate variability on the hydrological regime of Colombia have found: 1) Strong correlations between ENSO and hydrological variables, e.g.: greater variability in the monthly flow rate of the Cauca and Magdalena rivers; 2) Trends of increase / decrease in time of: air temperature, precipitation and monthly flow rate especially in the Andean region; and 3) that the probability distribution function of the maximum flow rate series is affected by both phases of ENSO (Ávila, Guerrero, Escobar, & Justino, 2019; Carvajal, Jiménez, & Materon, 1998; Gutiérrez & Dracup, 2001; Jiménez-Cisneros *et al*., 2014; Poveda, 2004; Poveda & Álvarez, 2012; Poveda *et al*., 2002;

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Poveda, Waylen, & Pulwarty, 2006; Puertas & Carvajal, 2008). Prior evidence has shown that the analysis of the hydrological risk associated with the ENSO phenomenon is key for flood management in Colombia, particularly in the Andean region where 80% of the population is concentrated.

At present, the debate on whether or not to adopt the assumption of stationarity required in hydrological statistics still continues (Matalas, 1997; Milly *et al*., 2015; Milly *et al*., 2008; Montanari & Koutsoyiannis, 2014). The discourse is antagonistic. On one hand, there is a call to incorporate non-stationarity in hydrological modeling to better represent reality; whereas others argue that multiple sources of uncertainty must be considered in order to ensure the stochastic approach remains robust. Although there is no consensus on the best analysis methodology, there are common points, such as: the need to increase the understanding of the climate-water-society system, reduce sources of uncertainty in the models, and above all, develop more robust analysis methodologies in order to propose effective, adaptive solutions to trends in hydrological risk change.

Many investigations have addressed non-stationarity in hydrological variables, via the development of non-stationary methodologies for the Frequency Analysis of extreme events, and propose adaptations to the concepts of return period and risk in hydrological design (Khaliq, Ouarda, Ondo, Gachon, & Bobée, 2006; Salas & Obeyskera, 2014). The most studied non-stationary models incorporate the forcing of trends using external covariates such as: climate variability indices, precipitation and temperature data; global change signals on a reduced scale, urbanization rates, reservoir rates, etc. This type of analysis aims to establish links between physical processes in the environment and changes in the distribution of probabilities associated with annual records of maximum flow rates. There are abundant references for the use of generalized additive models with the parameters of location, scale and form (GAMLSS), as a flexible alternative, both in the selection of the distribution function and the type of parameter trends (Ahn & Palmer, 2016; Córdoba, Palomino, Gámiz, Castro, & Esteban, 2015; Vasiliades, Galiatsatou, & Loukas, 2015; Villarini & Strong, 2014). Other works use Bayesian models and Singular Spectral Analysis (Escalante-Sandoval, & Garcia-Espinoza, 2014; Lima & Lall, 2011; Poveda & Álvarez, 2012).

All of the aforementioned, motivates the non-stationary statistical modeling of floods in Colombia. The evaluation of maximum annual flow rate in the Cauca River – located in the High Cauca Valley basin within the Andean region – was chosen as the case study. The region has a bimodal regime with rainfall between 1300 mm and 3000 mm, and has a floodplain of 840 km^2 susceptible to periodic flooding. Since 1985, flow rates in the river basin have been regulated by a reservoir. The Cauca River is of interest since it is one of the most urbanized regions of Colombia. In addition, between 1950 and 2015, 14 historical flood events in the Cauca River were recorded (Enciso, Carvajal, & Sandoval, 2016); six of these occurred after the construction of the reservoir (in 1988, 1997, 1999, 2008, 2010 and 2011) and coincided with La Niña phenomenon. The data corresponds to two hydrometric stations of

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interest, and was analyzed using the GAMLSS model proposed by Rigby and Stasinopulos (2005).

The hypothesis considers whether the use of non-stationary models present significant differences compared to stationary analysis, and aims to demonstrate that the incorporation of climatic forcing (through several macroclimatic indices associated with the South American tropics) and human activity (using a specific reservoir operation index) are suitable as additive terms that describe changes in the frequency and magnitude of maximum annual flow rate. The statistical models evaluated may be of interest to demonstrate opportunities for water resources management, especially the rules of operation for the reservoir to guard against flooding events, to the benefit of the city of Cali (the third most populous city in Colombia). Next, a characterization of the study area is presented, as well as the methodology used in the non-stationary frequency analysis. The results obtained are analyzed and some conclusions are summarized.

Study área

The high Cauca basin is located in southwestern Colombia. The Cauca river follows a south-north direction in an inter-andean valley (Figure 1). In the first 153 km, the channel descends 2.8 km to reach Salvajina

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reservoir, whose drainage area is 3,652 km^2. Downstream, the basin reaches 5,111 km^2 at La Balsa station and finally the area of interest closes at the Juanchito hydrometric station, covering a total of 8,556 km^2. Both stations were selected considering: 1) the proximity to the reservoir outlet, 2) Juanchito station is the control point for the volume operation in the Salvajina dam and 3) Juanchito is located on the outskirts of the city of Cali, which is the third most populous city in Colombia with 2.4 million inhabitants.

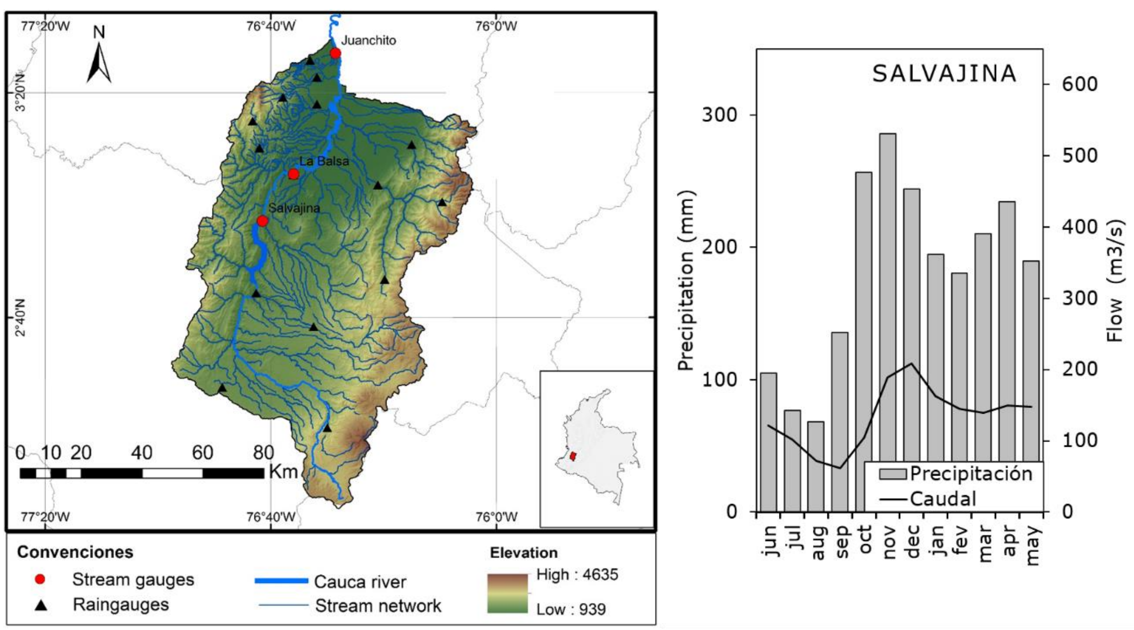

Figure 1. Location of the high Cauca basin and the hydrological network (left). Monthly rainfall in the area tributary to the reservoir and the tributary flow rate to Salvajina (right and above). Monthly storage in the Salvajina reservoir and average flow rate at Juanchito regulation target station (right and below).

The Salvajina reservoir has a maximum storage capacity of 848 hm^3, its operation objectives are flood and estuarine control, guaranteeing flow rates between 900 m^3 / s and 130 m^3 / s for 95% of the time at Juanchito station (Sandoval, Ramirez, & Santacruz, 2011).

The hydrological regime in the region is strongly affected by the climatic variability associated with the double passage of the Intertropical Convergence Zone (ITCZ), orography, the processes that occur in the Atlantic ocean, the Caribbean sea, the Pacific and the Amazon, but above all, by the influence of the ENSO phenomenon in its extreme phases (García, Botero, Bernal, Ardila, & Piñeros, 2012; Puertas & Carvajal, 2008; Rueda & Poveda, 2006).

Mean annual rainfall in the upper Cauca river basin is 1900 mm, and a bimodal cycle with greater rainfall predominates in the periods: March-April-May (MAM) and September-October-November (SON) (Figure 1, right) (Sandoval & Ramirez, 2007). Strong connections have been reported between mean monthly flow rates of various rivers in western Colombia with the El Niño Oceanic Index - ONI, and other signs of change in the surface temperature of the Pacific ocean, the Pacific Decadal Oscillation - PDO, with composite climatic signals for atmospheric and oceanic variables such as the ENSO - MEI Multivariate Index and exclusively atmospheric variables such as the Chorro del Chocó - CCC and the SOI Southern Oscillation Index, among others (Jiménez-Cisneros *et al*., 2014; Poveda, Jaramillo, & Vallejo, 2014; Poveda *et al*., 2006).

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Materials

All the hydrological and climatic variables were constructed considering that the hydrological year in Colombia begins on June 1 of year i and ends on May 31 of year $i+1$. 1965 – 2015 was defined as the common registration period since missing data was less than 5%. Finally, it is necessary to highlight that the 1985 data are adopted as atypical, due to the process of reservoir filling, and are therefore excluded from the hydrological and climatic series. The information was provided by the Regional Autonomous Corporation of the Valle del Cauca (CVC). The time series analyzed is the maximum daily flow rate recorded per hydrological year in m^3 / s - Q_{max}. Next, other data used in this work are described.

Reservoir index

López and Francés (2013) propose an IE reservoir index (Equation 1), which establishes the degree of alteration of the hydrological regime based on the percentage of unregulated area, and the percentage of average runoff that cannot be retained in the reservoir.

$$\text{IE}\ (t) = \sum_{i=1}^{N} \frac{A_{R_i}(t)}{A_s} \cdot \frac{C_{Ri}(t)}{C_s}\ , for\ i = 1,2,3, \dots, N. \qquad (1)$$

Where, $A_{R_i}(t)$ is the tributary area to the reservoir in km^2, in year t, A_S is the area tributary to the station in km^2, C_S is the mean volume drained in the basin to station S in the year t and in hm^3, C_R is the total storage capacity of the reservoir in hm^3 in year t; and N the number of reservoirs upstream of the station. For a basin with a single reservoir at the head and without other significant anthropic changes over time (eg transfer, increase / decrease of reservoirs, etc.) that affect the variables $A_{R_i}(t) A_{R_i}(t)$ y $C_{Ri}(t)$, this Index works as a discrete variable or change signal that is intense / weak depending on the proximity of the capacity station of interest to the dam, and has been used in statistical non-stationary flood modeling (Liang, Jing, Wang, Binquan, & Zhao, 2017; Machado *et al*., 2015).

The impacts of a reservoir on the rolling of floods depends upon: the available capacity of the reservoir, the size of the works in relation to basin water supply, the uses of stored water and water levels in the reservoir before the channel, etc. (Moreno, Begueria, Garcés, & García, 2003). Available capacity means the free volume or difference between the maximum storage capacity and the volume of water at any given time. Changes in available capacity may limit / favor the management of

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maximum annual flow rates at the target station. Therefore, in this paper it is proposed to adjust equation 1, replacing the relationship between reservoir capacity and average runoff, by the annual reserve volume coefficient $D_{(t)} = \left(C_{R(t)} - V_{a(t)}\right)/C_{R(t)})$ that determines the proportion of volume available versus the capacity of the reservoir, so that the index IE_2 is:

$$IE_2(t) = \sum_{i=1}^{n} \frac{A_{R_i}(t)}{A_s} \cdot \frac{C_{R\,(t)} - V_{a\,(t)}}{C_{R\,(t)}},\ for\ i = 1,2,\ldots,N \qquad (2)$$

Where $V_{a(t)}$ is the mean annual volume stored in the Salvajina reservoir, estimated with data from bathymetry conducted by the CVC in 1985, 2003 and 2011, and the reservoir end-of-day level records. With this change, in addition to the effect of a decrease in regulatory capacity as the tributary area at the capacity station increases (established by the ratio of areas), the index considers volume management as a condition that influences observed maximum annual flow rates.

Indices of climatic variability

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Bearing in mind that the ENSO phases are defined by the US National Ocean and Atmosphere Agency (NOAA) based on the El Niño Oceanic Index (ONI), in this work the mean annual value of ONI is adopted as a criterion to classify each hydrological year, as follows: one year is considered La Niña if the ONI mean annual value ≤ -0.30; El Niño years occur when $ONI \geq 0.30$; and a year is defined as Normal, provided that $-0.30 < ONI < 0.30$. The low frequency climatic indices used in the modeling correspond to the mean annual values of the El Niño Oceanic Index - ONI or quarterly moving mean of the anomalies of Pacific surface temperature in the Niño3-4 region and the ENSO - MEI Multivariate Index, which corresponds to the First Principal Component of a set of oceanic and atmospheric signals throughout the Tropical Pacific region. All values are estimated based on information published by NOAA (2017).

Generalized Additive Models of Location, Scale and Shape parameters-GAMLSS

GAMLSS models assume that the response variable Y (Q_{max}) has a cumulative probability distribution function, whose parameters may be a function of one or more explanatory variables (climatic and reservoir indices). That is, for y_t independent variables at time $t = 1,2, \ldots, n$; there is a function $F_Y(y_t|\theta_t)$, where the parameters $\theta_t = (\mu_t, \sigma_t, \upsilon_t, \tau_t)$ can change based on a set of m explanatory variables $X_{mt} = [x_{1t}, x_{2t}, \ldots, x_{mt}]$ through a monotonic link function $g_k(\theta_k)$ presented in Equation (3) (Stasinopoulos, Rigby, Vlasios, Heler, & Bastiani De, 2015):

$$g_k(\theta_k) = \eta_k = X_k\beta_k + \sum_{j=1}^{m_k} h_{jk}(x_{jk}) \qquad (3)$$

Where θ_k and η_k are vectors of length n; X_k is an array of covariates of order $n\ x\ m$; β_k is a vector of parameters of length m; $h_{jk}(x_{jk})$ represent smoothing in the distribution parameters; and x_{jk} is a vector of covariates for $j = 1,2, \ldots, m$.

As a smoothing function, the B-splines, $pb\,()$ which are polynomial parts used in additive models, are evaluated, with the advantage that they minimize the degrees of freedom (df) of the model, through different methods e.g.: Maximum Likelihood (ML), GAIC, etc. More information can be found in Stasinopoulos *et al*. (2015).

Non-stationary return period

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The return period T is an indicator of the rarity of flooding, that is, the average time that elapses until, for the first time, a flood exceeds a given value ($y_{\mathrm{p}0}$). It is commonly used to define the design flow rate of a hydraulic work or to reference the level of flood threat. Considering that the statistics of this event follow a geometric distribution, the probability that the first flood exceeds y_{q0} at time x is $f(x) = p_x \prod_{t=1}^{x-1}(1-p_t)$, $x = 1,2,\ldots,x_{max}$ (Salas & Obeyskera, 2014), where $f(1) = p_1$ and x_{max} is the time at which p_t becomes unity. If the probability p_t is constant over time $f(x) = P(X = x) = (1-p)^{x-1}p$, therefore, the return period or Expected Wait Time (*EWT*) is:

$$T = E(X) = 1/p = 1/(1-\mathrm{q}) \qquad (4)$$

Where p and q are the probability of exceedance and without exceedance, respectively. When the probability p_t is non-stationary, then the return period changes over time:

$$T_t = \frac{1}{p_t} = \frac{1}{[1-F_Y{}^{-1}(y_{\mathrm{p}0},\theta_t)]} \qquad (5)$$

The values of the probability of exceedance p_t are obtained from $p_t = 1 - F_Y(y_{q0},\theta_t)$ using the available data. $y_{\mathrm{p}0}$ is a reference flow rate for a non-stationary Frequency Analysis model of which the parameter θ_t varies in accordance with the covariates X_{mt} (Obeyskera & Salas, 2016).

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Considering Equation (5), in the hydraulic design and management of water resources, questions arise: What is the value of T of a historical event, associated with a non-stationary flood model? What is the design flow rate, if the value of T is variable in time? Because of this, Salas and Obeyskera (2014) propose to determine the non-stationary T value, using a non-homogeneous geometric distribution:

$$T_{EWT} = E(X) = 1 + \sum_{x=1}^{x_{max}} \prod_{t=1}^{x} (1 - p_t)\,,\ x = 1,2,\dots,x_{max} \qquad (6)$$

Where the values $p_t = 1 - q_t$, are obtained from $p_t = 1 - F_Y\left(y_{q0}, \theta_t\right)$, for the preset y_{q0} and the non-stationary statistical model. Salas Obeysekera and Vogel (2018), and Serinaldi (2015) present another simplified way of estimating the non-stationary return period, based on the concept of "Average Annual Risk" economic analysis (AAR) expressed as: $AAR(n) = \bar{p} = (1/n)(p_1 + p_2 + \cdots + p_n)$. Where it is assumed that for a period n, the risk can be described by the mean of the sequence of probabilities of exceedance $(p_1, p_2, \dots, p_n)$, due to this, non-stationary T equals:

$$T_{AAR} = \bar{T} = 1/AAR(n) = 1/\bar{p} \qquad (7)$$

Serinaldi (2015) argues that one of the most important indicators in the planning and design of hydraulic works is the Risk of Failure R or probability R that an extreme event will be observed at least once y_{q0}

during the useful life n of a works. This expression being the most appropriate or direct to define the design flow rate against an acceptable level of risk since it depends on the probability of exceedance and not on the return period. When i.i.d. conditions exist, i.i.d. $R = P(X \leq n) = F_X(n) = \sum_{x=1}^{n} f(x) = 1 - (1-p)^n$ (Chow, Maidment, & Mays, 1994); however, under conditions of non-stationarity Salas *et al*. (2018) use the concepts Expected Wait Time and Average Annual Risk to determine the risk of non-stationary failure:

$$R_{EWT}(n) = 1 - \prod_{t=1}^{n}(1-p_t), \qquad (8)$$

$$\overline{R_{AAR}} = 1 - (1-\bar{p})^n \qquad (9)$$

Where p_t and $\bar{p}$ are the probability of exceedance and the probability of multi-year mean exceedance, respectively. Highlighting that R_{EWT} and R_{AAR} are solved numerically.

Methodology

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Statistical modeling of the frequency and magnitude of hydrological extremes is based on the generalized additive models of location, scale and the GAMLSS form. All calculations can be executed in the R program, using the available free GAMLSS packages. The analysis has the stages of Figure 2.

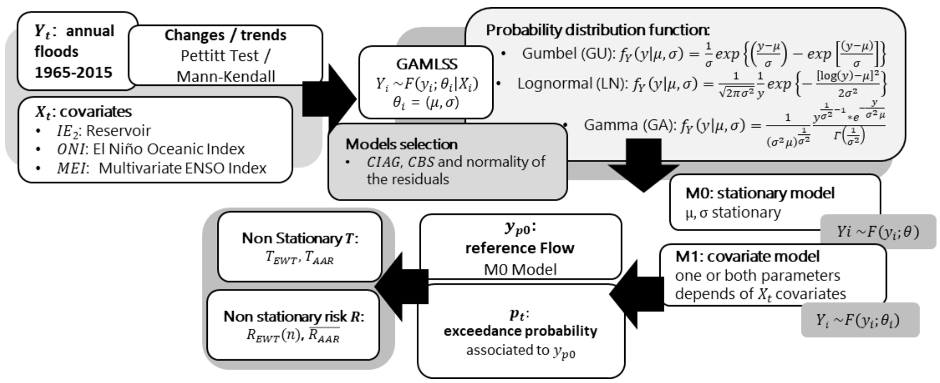

Figure 1. Flow chart of the stages that make up the non-stationary frequency analysis.

Identification of changes and trends in the flood regime

The non-parametric statistical tests of Mann-Kendall (Mann, 1945; Yue & Wang, 2002) and Pettitt (1979) are applied to the time series to analyze the stationarity. Additionally, in order to address the effects of reservoir

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operation, the maximum annual flood series were divided into the periods: 1965-1984 and 1986-2015, thereby representing the unregulated regime and the altered regime, respectively.

Adjustment and selection of non-stationary statistical models

GAMLSS models are used to force gradual changes in the location parameter (μ) based on the *ONI, MEI* and *IE2*. covariates. The probability distribution functions selected are: Gumbel (GU), Lognormal (LN) and Gamma (GA). All have two parameters (μ, σ), they are suitable to counteract the effects of positive asymmetry, common in series of hydrological extremes. The results will focus on the best models obtained and not on the set of models evaluated.

Two types of statistical models are analyzed: Stationary models (M0), where both distribution parameters are independent; and the models of external covariates (M1), in which the location parameter μ can depend linearly on one or several climatic indices, on the reservoir index or on the combination of both types of explanatory variables. The selection of the models is based on the Generalized Akaike Information

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Criteria (GAIC) and the Schwartz Bayesian Criteria (*SBC*) (Equation (10) and Equation (11)):

$$GAIC = -2\,\hat{l} + 2\,(k\,.df) \qquad (10)$$

$$SBC = -2\,\hat{l} + \ln(n) * (k.df) \qquad (11)$$

Where $\hat{l} = ln\,(ML)$, the maximum likelihood of the model is ML, then k: required penalty associated with the number of parameters of the distribution and df: degrees of freedom. In this work, a penalty $k = 3.0$ is adopted, in such a way that the degree of complexity of the model does not degrade the ability to describe the behavior of the series and conserves as much as possible the principle of parsimony.

In the absence of a statistic to determine the goodness of fit of the GAMLSS models, Stasinopoulos *et al*. (2015) propose to verify the normality of the residuals, for this the Filliben correlation coefficient and the behavior of the graphs without the residuals trend (*worm-plot*) are evaluated. This ensures that the selected model represents the systematic part and that the remaining (residual) information is white noise.

The return period in non-stationary models

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To compare the results obtained in the M0 and M1 models, the EWT and AAR formulations are used. The calculation starts by defining a flow rate y_{p0} with the stationary model, then the non-stationary model M1 is used to estimate the probability of exceedance, equations 4 to 9 are applied to determine the hydrological risk in terms of non-stationary *T* and R, considering between other aspects: the moment at which p_t becomes unity, the length n of records and the predominant pattern of change in M1. It is important to mention that, for each station, R is estimated for the design flow rate of *T* = 100 years and different values n of working life.

Results and discussion

Altered flood regime

Next, the changes in the flood regime in La Balsa and Juanchito are analyzed.

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Table 1 confirms that the flow rate at La Balsa decreases during the registration period and this trend is significant at $\alpha = 0.05$. In addition, there are points of change in the mean in 1975 and 1984 that coincide with phase changes of the PDO and the commissioning of the reservoir. Due to the proximity of the station to the reservoir output it is possible to associate the non-stationarity with anthropic alteration. Figure 3b shows the decrease in the magnitude of Juanchito's floods between 1965 and 1984, but this change has no statistical significance (Table 1). On the contrary, between 1986 and 2015, a gradual and significant increase in annual maximum flow rate is observed, although this increase does not necessarily respond to a linear correlation (Figure 3b). There are also identified points of change in the mean in 1984 and the 1970s and 1990s that coincide in the first moment with the commissioning of the reservoir, and the rest with PDO phase changes, a high rate of occurrence of ENSO events (five reported in the 1970s and 1980s) (Wolter & Timlin, 1998), and historical floods of the Cauca river in 1971, 1974, 1975, 1982, 1984, 1988, 1997 and 1999, 2008, 2010 and 2011 (Enciso *et al*., 2016), that affect the mean of the time series.

Table 1. Results of the homogeneity hypothesis tests for the annual maximum daily flow rates in the Cauca River.

Station			**La Balsa**			**Juanchito**		
Series	**Test**	**Period**	**65-15**	**RN**	**RA**	**65-15**	**RN**	**RA**
Qmax	M-K	τ	-0.33*	-0.38	-0.04	-0.06	-0.02	0.22*

		Sig.	P1	P5	NS	NS	NS	P10
	Pet	Year	1984	1975	1991	1984	1975	1994
		Sig.	P1	P5	NS	NS	NS	P5

RN: 1965-1984, RA: 1986-2015. M-K: The Mann-Kendall test; τ is the statistic test and its sign indicates the direction of the slope. (*) Indicates that the Mann-Kendall tests include processes to remove the serial dependency. Sig.: statistical significance, NS: not significant, P1: significant at 1%, P5: at 5% and P10: at 10%. Pet: Pettitt test; Year: moment of abrupt change in the mean.

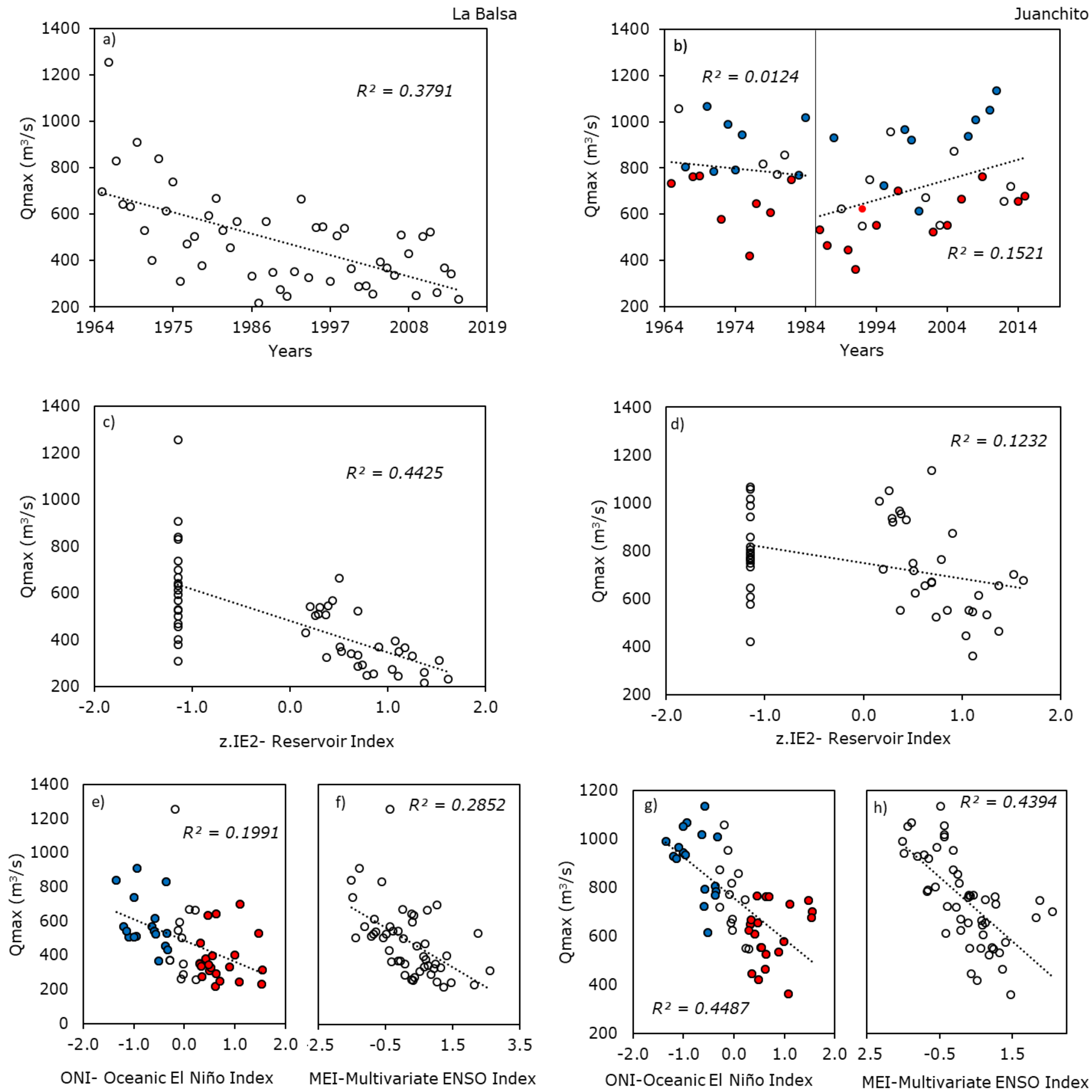

Figure 3. Variation of annual floods. From left to right La Balsa and Juanchito; a), b) time evolution; c), d) Connection with the IE2 reservoir index; e)-h) Relationship with the ONI and MEI indices, highlighted in blue and red the flow rates observed in La Niña and El Niño years, respectively.

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The following physical processes that may be related to the trends of increase in the flood regime of Juanchito station between 1986 and 2015 are:

- Changes in land use in the last 30 years that affect the runoff of tributary rivers downstream of the reservoir. Given that 43% of the total drainage area to Juanchito corresponds to the reservoir basin, it is consistent to consider that important tributary rivers that are not currently regulated make a strong contribution to runoff in the area. Also, there is evidence of increased precipitation in that region. Ávila *et al*. (2019) analyzed the time series of extreme climatic precipitation indexes in 39 meteorological stations of the Alto Cauca Valley in the period 1970-2013. They recognized that for a statistical significance $\alpha = 0.10$: the accumulated precipitation in one and five consecutive days increases between 40 - 80 mm in the south region of the western Andes mountain range (between the reservoir and Juanchito). This coincides with the Climate Change projections that foresee a 6% increase in total rainfall in the climatic models of Valle del Cauca, from the periods 2011-2040, 2041-2070 and 2071-2100 (IDEAM et. al, 2015). If, in addition, it is considered that the La Niña phenomenon increases and prolongs high flow rates, it is to be expected that the effect of the reservoir on the control of floods is limited and that the floods are largely due to the contribution of the unregulated tributary rivers.

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- Between 1986 and 2015, seven historical floods have been recorded in La Niña years (Enciso *et al*., 2016). Of these floods, four occured simultaneously with the cold phase of the PDO. Of all recent floods, those occurring in 2010-2011, are recorded during one of the most severe La Niña events in recent history (NOAA-ESRL-PSD, 2017).
- Until 1975, and then between 1999 and 2014, cold phases of the Pacific Decadal Oscillation (PDO) prevailed (JMA & WMO, 2017; Herzog, Martinez, Jorgensen, & Tiessen, 2012; NOAA, 2017). There are several references on the simultaneous action of ENSO and the PDO on the hydrological regime in various regions of the world that establish that the effects of El Niño / La Niña events are stronger and occupy a larger global space area when they occur in phase with hot / cold periods of the PDO (Garreaud, Vuille, Compagnucci, & Marengo, 2009; Méndez, Ramírez, Cornejo, Zárate, & Cavazos, 2011; Wang, Huang, He, & Guan, 2015). This shows the need for more research on the joint action of different signs of climate variability and the hydrology of the Colombian southwest.
- Changes in the hydrometric stations and / or in the way of processing the data could also be another explanation for the abrupt changes observed (Villarini *et al*., 2009a).

The results obtained in Table 1 highlight the difficulty in accepting / rejecting the i.i.d. hypothesis for the 1965-2015 period at Juanchito station, since the non-parametric tests applied indicate stationarity. However, changes in the slope of the trend lines in the RN and RA periods mask the continuous increase in annual flooding in the last 30 years of

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the analysis period and therefore, the RA sample requires the non-stationary Flooding Frequency Analysis.

Figure 3 shows the behavior of maximum annual floods as a function of time and reservoir and climate indices, which suggest that although there is a moderate linear correlation $(0.30 < r < 0.70)$, the variability explained by the selected indices is low. This is understandable, given the complex connection between flow rates and climatic variables that do not necessarily conform to linear models, therefore, it may be necessary to include smoothing functions in non-stationary statistical modeling.

Non-stationary statistical models of the flood regime in the Cauca River

The results of the statistical modeling of the annual maximum daily flow rates for La Balsa (1965-2015) and Juanchito (1986-2015) are presented below.

Table 2 shows that the stationary model (M0) in La Balsa follows the Lognormal distribution (LN2). The *Log* transformation helps reducing the positive asymmetry of the observations. Then, the floods in Juanchito conform to the Gamma distribution, which is a function that has a smooth form and does not require the *Log* function to counteract the asymmetry;

This last result is similar to that obtained by Enciso *et al*. (2016), who finds that Juanchito's annual maximum daily flow rates in the 1986-2015 period are adequately adjusted to a Log Pearson III distribution, which is a generalization of the Gamma distribution. Next, it can be seen that the GAIC statistic suggests that the M1 models have lower loss of information. Regarding the quality of fit, in all cases, the Filliben correlation coefficients are higher than the critical values, therefore, the hypothesis of normality in the residuals is accepted and the models are adequately adjusted to the observations.

Table 2. Summary of the selected and statistical models of GAMLSS residuals of the annual maximum floods in the Cauca River.

Variable Station Period Distribution	**Model**	**Parameters [Error St.]**	**CIAG**	**C.F.**
Qmax La Balsa 1965-2015 LN2, n=50	M0	$\mu_1 = 6.1\,[0.05]$, $\sigma = -0.94[0.10]$	664.01	0.991
	M1	$\mu_1 = 6.10\,[0.04]$, $\mu_2 = -0.28IE2\,[0.04]$, $\sigma = -1.30[0.10]$	<u>631.05</u>	<u>0.996</u>
Qmax Juanchito 1986-2015 GA, n=30	M0	$\mu_1 = 6.58[0.05]$, $\sigma = -1.31[0.13]$	405.85	0.988
	M1	$\mu_1 = 6.75[0.07]$,$\mu_2 = -0.12pb\,(MEI)\,[0.05]$, $\mu_3 = -0.21IE2[0.10]$, $\sigma = -1.84[0.13]$	<u>385.68</u>	<u>0.993</u>

The non-stationary model of the LN2 and GA distributions have as linking function the localization parameter: $\ln(\mu_t) = \mu_1 + \mu_2 X_i + \cdots + \mu_n X_m$ as a function of the $X_1, X_2, \ldots X_m$ covariables and the constant scale parameter is expressed as: $\ln(\sigma_t) = \sigma$. In addition, GAIC is the Generalized Akaike Information Criteria for a penalty ratio $k = 3$; and C.F. is the Filliben correlation coefficient applied to the residuals ($Fill_{n50,\alpha 0.05} = 0.977$; $Fill_{n30,\alpha 0.05} = 0.964$).

Debele, Bogdanowicz and Strupczewski (2017) suggest that the selection of the distribution function (fdp) is one of the most important decisions for the proper analysis of the models. We consider that the hypothesis tests establish an adequate fitting, but do not necessarily lead to the selection of the best fdp. For this, GAMLSS models provide a broad range of comparison options between different families of fdp and also the consideration of non-stationarity. However, it is necessary to use the expert's criterion to select a pfd that controls the effect of the positive asymmetry characteristic of the hydrological series and a model without over-parameterization.

Among non-stationary models with the best fit we have: a) The temporal variability of the floods at La Balsa station is explained through the IE2 reservoir index. This is due to the fact that La Balsa has the smallest area of total contribution and since it is located near the reservoir output, the anthropic regulation predominates over the change patterns of the series; b) The maximum flow rates at Juanchito for 1986-2015 have a non-linear dependence on the MEI index through $pb()$ smoothing and linear to IE2. Different publications indicate that GAMLSS with climatic forcing are significant to represent changes in the frequency and magnitude of floods in different regions of the planet (Machado *et al*., 2015; Obeyskera & Salas, 2016; Villarini, Smith, Serinaldi, Ntelekos, &

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Schwarz, 2012). In this work, the ENSO signals and the proposed reservoir index are adequate to link anthropic and climatic effects to patterns of the annual flood series for the southwest of Colombia. In addition, it is possible that as the station moves away from the reservoir, the effect of climate variability becomes more significant as an explanatory variable.

It is important to highlight that based on the evidence of non-stationarity, it is necessary to adopt methodologies that incorporate change patterns and allow a comparative analysis of results. In this work, the non-stationary models based on co-variables (M1) show a better representation of the variability of the time series, considering that the majority of the observations are within the band of quantiles 1% to 99% of the models (Figure 4a and Figure 4b). Villarini, Serinaldi, Smith, & Krajewski (2009b) obtained similar results using GAMLSS for the analysis of floods in a US basin, mentioning that the models manage to capture the wide dispersion and nonlinearity of data for percentiles between 5 and 95%.

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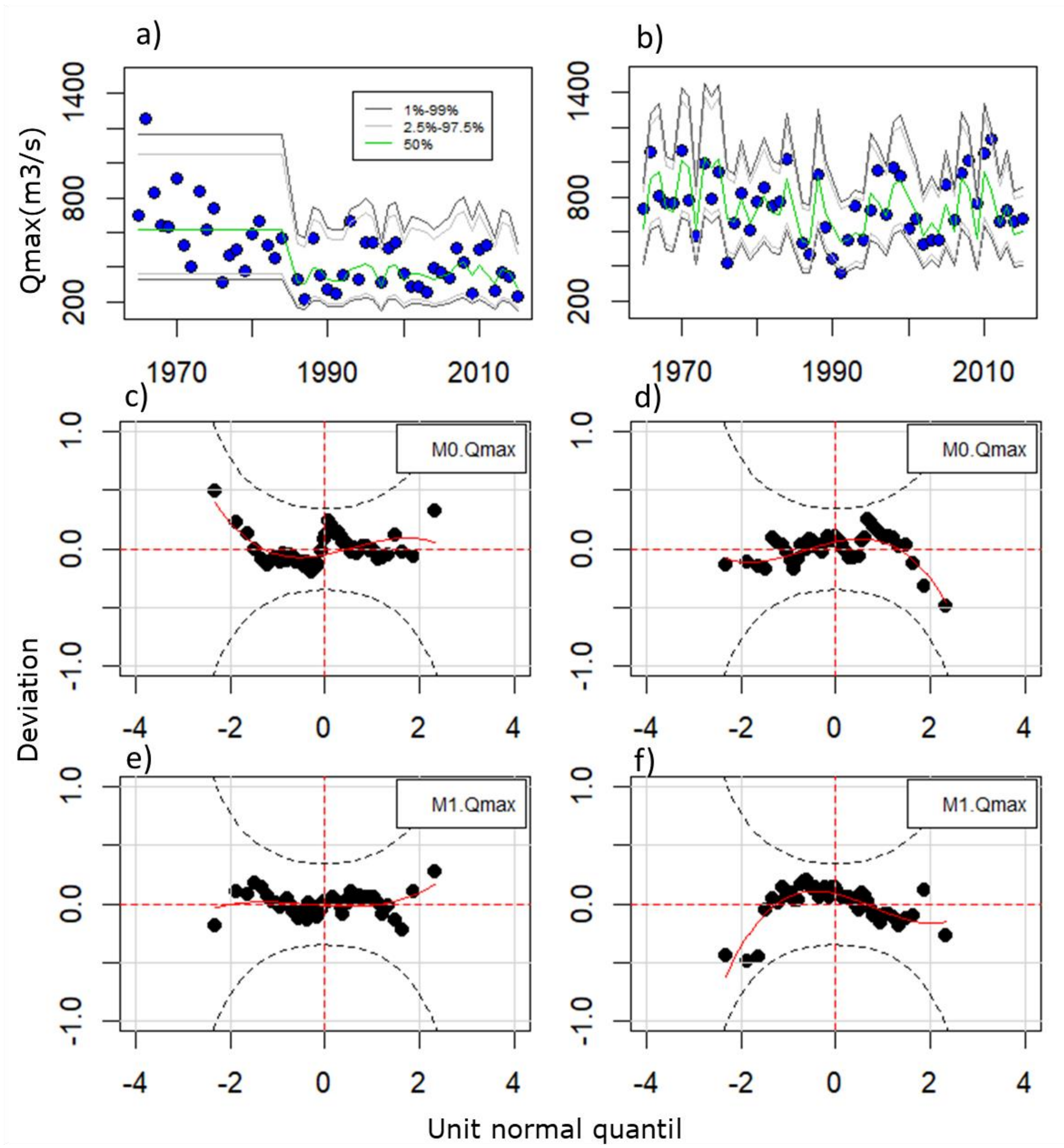

Figure 4. Statistical models. From left to right: annual floods at La Balsa and Juanchito; a) and b) the temporal variation of different percentiles in the range 1% - 99% of the M1 model (solid lines), the blue dots correspond to the observations. Theoretically, between 60%

and 90% of observations are expected to be within the area covered by the 1% and 99% percentiles of the model; c)-f) contain the worm-like graphics of the residuals of the M0 and M1 models, respectively.

The non-stationary M1 models show - for all the percentiles plotted - that at certain times the magnitude of the variables obtained is different from that estimated under stationary conditions, e.g. during La Niña years, and that increases in the magnitude of flow rates that can affect flood risk indicators such as the return period and the risk of failure for a particular project life can be identified. Regarding this result, López and Francés (2014), when evaluating floods in the Northwest of Mexico, also find a significant influence of the ENSO phenomenon in the inter-annual variability of the flood regime, highlighting increases in magnitude during La Niña. In addition to the above, it is necessary to recognize that a limitation of the results of the co-variable models is the uncertainty associated with ignorance about the future, e.g. the behavior of the explanatory variables beyond the registration period (there are no long-term projections for the ENSO indices that may be incorporated into the predictive power of the models) and that other physical processes (not considered in the present study) may be more significant to describe the variability of floods.

Figures 4c-4f evaluate the normality of the residuals of the different models based on their configuration. In a Q-Q graph with no tendencies, which is usually shaped like a worm, one seeks for the continuous red line (trend) to be similar to a straight line, parallel and close to the horizontal

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axis. On the contrary, when the residuals show accentuated configurations either in S or U, they indicate high asymmetry and / or kurtosis (Buuren & Fredriks, 2001). In both stations, it is evident that the models meet the normality condition. However, of all of them, the M1 model of La Balsa has fewer deviations from that assumption.

Analysis of changes in the return period

Figure 5 and Table 3 show the variations obtained when estimating the period of return T and risk of failure R, for the selected stationary and non-stationary models. Figures 5a and 5b contain the variation of non-stationary T as a function of stationary T, following the methods of Expected Wait Time (*EWT*) and Average Annual Risk (AAR) (Salas *et al*., 2018). This paper establishes that the maximum annual flow rates at La Balsa have a long-term tendency to decrease, so that the probabilities of exceedance also suggest a decreasing pattern. Figure 4a establishes the variation of non-stationary T, highlighting two things: first, for $1 \leq T \leq 5$ years, the non-stationary model indicates that $T_{EWT} < T$. This corresponds to an increase in the probability of observing minor floods. However, when using the AAR method, no differences can be seen between non-stationary T and $T \leq 20$ years, ($T_{AAR} \cong T$), this situation can

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be associated with the fact that in the first 20 years of records (1965-1984) the hydrological series was not affected by the reservoir, so the mean of the probability of exceedance remains constant and similar to that of the stationary model. Second, from the aforementioned inflection points, it is appreciated that $T_{EWT} > T$ and $T_{AAR} > T$, thus, the decrease in the magnitude of the floods during the altered regime (1986-2015) leads to the decrease in hydrological risk expressed as the probability of observing a flood equal to that of the reference or increase in non-stationary T. Said behavior of increase and subsequent decrease of the hydrological risk can be seen directly in Figure 4c where the risk of failure R associated with a T=100 years flood flow rate or the probability of observing, at least once, a flood equal to that of the reference in a period of n years of working life. In the case of La Balsa, a $R_{EWT,AAR}$ larger than the stationary is observed for works with $n < 20$ years and a lower risk, from 30 years of working life. Another aspect to note is that the non-stationary R values in each station are identical regardless of the method of determination, so their use could be a more direct way of establishing the design flow rate of a hydraulic works for a predefined acceptable level of risk.

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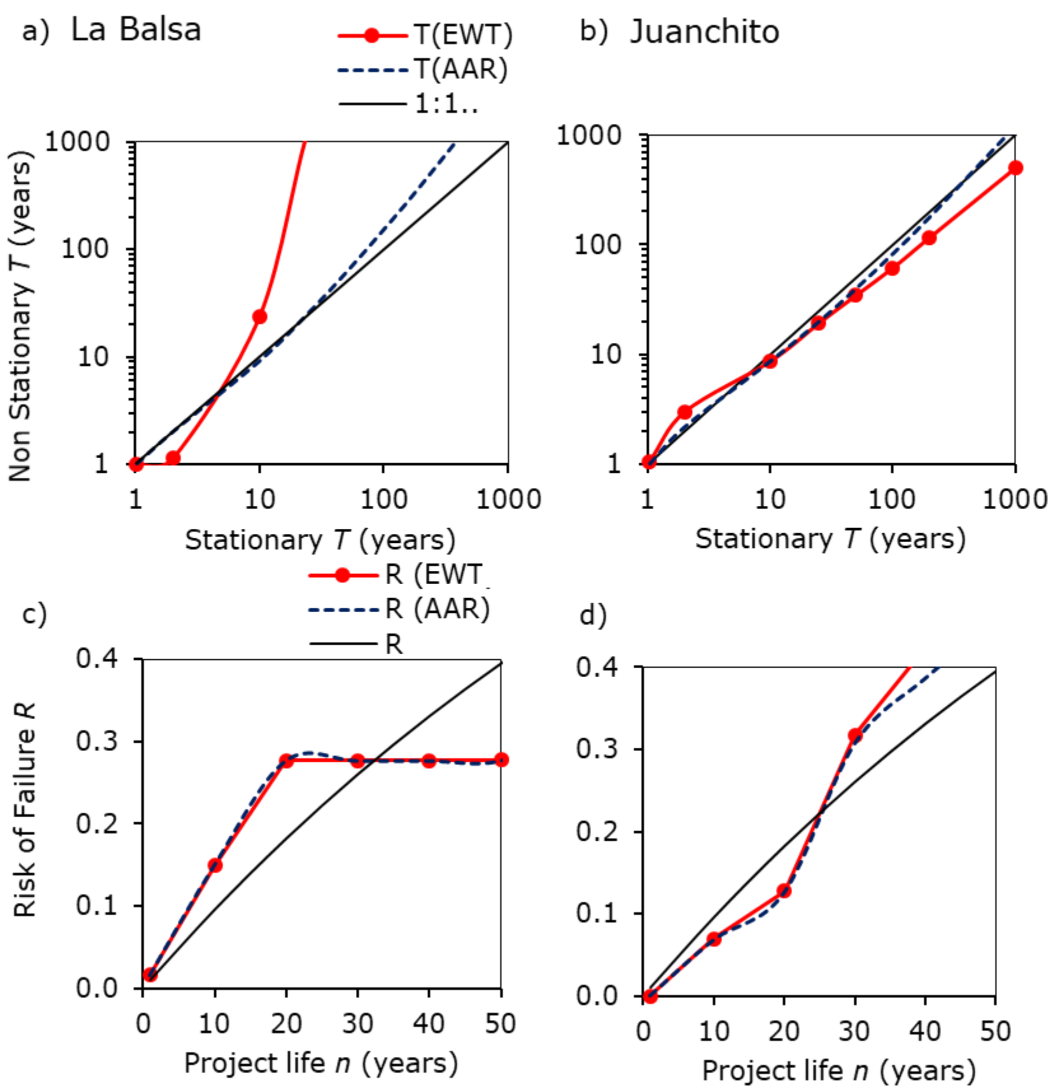

Figure 5. Variation of the Return Period and Risk of Failure of the statistical models of La Balsa (left) and Juanchito (right). Above, evolution of non-stationary *T* as a function of stationary *T*. Below, changes in risk as function of working life.

Table 3. Comparison between the period of stationary and non-stationary return for several flood flow rates.

Station	La Balsa							
Qmax (m3/s)	212	445	735	883	995	1107	1221	1494
T (years)	1	2	10	25	50	100	200	1000
T(EWT)(years)	1	1	24	1363	4410	7227	8829	9881
T(AAR)(years)	1	2	9	26	62	155	402	4143
Station	**Juanchito**							
Qmax (m3/s)	397	700	975	1091	1171	1246	1316	1470
T (years)	1	2	10	25	50	100	200	1000
T(EWT)(years)	1	3	9	19	34	61	116	497
T(AAR)(years)	1	2	9	20	40	82	178	1194

In the case of annual floods at Juanchito between 1986 and 2015, an increasing trend has been described (Figure 3b). When comparing the non-stationary return period, Figure 5b shows: 1) When $1 < T < 7$ years $T_{\text{EWT}} > T$ and $T_{\text{AAR}} > T$ are obtained. Therefore, the co-variable model indicates that the most frequent floods have a lower probability of occurrence in comparison with the stationary model. After seven years, the opposite occurs: $T_{EWT} < T$ and $T_{AAR} < T$. Although graphically this difference is modest, the decrease of T_{EWT} against T ranges between 14% and 50%, whereas between T_{AAR} and T varies between 15% and 39%, with a slight increase when T is 1,000 years. Among the possible explanations for the evolution of T_{AAR} are the gentle slope of change of

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the annual maximum flow rates, its significance ($\alpha = 0.10$) and the short length of the time series (30 years). In any case, the information obtained highlights a slight increase in the probability of occurrence of extreme maximum floods. Which leads us to consider that although the management of the reservoir has positive effects on the most common floods, there are external factors (climatic variability, increase in precipitation, changes in the unregulated basin, etc.) that negatively affect the objective of regulation of the rarest and most extreme floods. Similar information is presented in Figure 5d, in which case $R_{EWT,AAR} < T$ for a working life of $n \leq 25$ years, but from said n, the risk failure of the non-stationary model exceeds that of the stationary R.

All the changes in the hydrological risk indicators ($Qmax$, T y R), are of interest for flood management at Juanchito, not only because this is the target station for volume control in the Salvajina reservoir; but because the unplanned urban growth in the city of Cali, as in many other cities in developing countries, has led to intensive building developments in the flood plains of both banks of the Cauca River. About 900 thousand inhabitants of the city are located in a flood risk area on the right bank of the Cauca river. Flood control is managed through the operation of the reservoir and lateral levees built for a T=30 year flood. Despite these structures, the changes in the hydrological risk identified are corroborated by historical flow rates observed in 2008, 2010, 2011 and 2017; and more than ten floods in the Juanchito area recorded in the last decade (El País, 2011; Enciso *et al*., 2016), highlighting the need to provide for a natural disaster risk management program that incorporates a systemic view of

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the problems and includes change patterns associated with climate variability.

Conclusions

In this work, the effects of reservoir operation and climate variability as patterns of alteration of the annual flood regime are analyzed with the Non-Stationary Flood Frequency Analysis, using GAMLSS models. The main conclusions are.

Daily flow rate records between 1965 and 2015 at La Balsa station point to a significant decrease ($\alpha = 0.05$), in the magnitude of annual floods. Abrupt changes and gradual trends are associated with the phase change in the PDO in the 1970s, to severe meteorological droughts recorded in Colombia between 1970 and 1990, but above all, to the construction and commissioning of the reservoir in 1985.

Maximum annual floods at the Juanchito station between 1965 and 2015, show a pattern of significant increase ($\alpha = 0.10$) in the last 30 years of records (1986-2015), that has been masked by the behavior of the observations between 1965 and 1984. This may partially explain how, despite the regulation of flood flow rates, seven events of historical

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magnitude were reported between 1986 and 2015, with the one observed in 2010-2011 being the most severe of all with a flow rate of 1,135 m^3 / s. All of the above leads to consider not only the importance of analyzing trends in samples of the hydrological series, but also to reflect on the need for adjustments in basin management plans.

The increase in the magnitude of maximum annual flow rate at Juanchito may be associated with the close connection between the prolonged and strong floods and climatic events, which in conjunction with the cold phase of the PDO strengthens the nuclei of maximum rainfall in the study area. This information shows the need for more research to establish the type of connection and the effects that the joint action of the PDO and ENSO have on the hydrology of the Colombian southwest. Additionally, it is likely that land use changes in the area tributary to Juanchito that are not regulated by the reservoir (57% of the total area), also affect the trends of increased runoff.

For all the stations evaluated, the study demonstrates that the use of additive terms improves the description of changes to the frequency and magnitude of floods, accepting the hypothesis of significant differences between stationary and non-stationary models.

The non-stationary statistical modeling of the annual maximum daily flow rates uses the IE2 covariate to describe the changes at La Balsa station, and the set of MEI and IE2 indices to explain the behavior over time of the floods at Juanchito, achieving the objective of the study. The proposed new reservoir index helps improve the representation of flood variability. Despite the uncertainty of the results, the new information can contribute to a more robust selection of flow rates design and the acceptable threat and risk ranges.

This article manages to assess the EWT Expected Waiting Time and AAR Medium Risk Analysis methods to determine the non-stationary return period and risk of failure, both indicators are able to adequately capture the changes in the probability of exceedance and therefore work as new flood risk indicators. Regardless of the method of determination, the less frequent or rarer floods are identified: i) a higher T and lower R non-stationary for the maximum floods in La Balsa; and ii) in Juanchito, the increase in the probability of exceeding a maximum annual flow rate leads to a decrease in T and an increase in non-stationary R.

Finally, all the above information is of interest in flood risk management in the Cauca River High Valley, for example, it can influence the sizing of flood protection works, the design of storm drain discharge works of Cali, lead to changes in the zoning of the degree of threat and flooding risk, and may have implications for land use; but above all, it shows the need to incorporate both the effects of ENSO, and non-stationarity, in the operating rules of Salvajina reservoir. However, it is important to mention that flood management must have a comprehensive framework of available measures, natural resources management, future visions and environmental constraints.

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