INGENIERÍA AGRÍCOLA

Análisis hidrológico de las crecientes históricas del río Cauca en su valle alto

AGRICULTURAL ENGINEERING

Hydrological analysis of historical floods in the upper valley of Cauca river

Angélica M. Enciso*, Yesid Carvajal-Escobar*§, María C. Sandoval**

**Engineering School, Natural and Environmental Resources Engineering School, IREHISA Research Group, Universidad del Valle. Cali, Colombia.*
***Environmental Technical Direction, Hydric Resources Group, Corporación Autónoma Regional del Valle del Cauca (CVC). Cali, Colombia.*
§yesid.carvajal@correounivalle.edu.co, angelicaencisoarango@correounivalle.edu.co, maria-clemencia.sandoval@cvc.gov.co

(Recibido: Enero 09 de 2015 – Aceptado: Agosto 13 de 2015)

Resumen
El río Cauca es la principal fuente hídrica superficial del Valle del Cauca y en los últimos 25 años ha registrado importantes crecientes causando inundaciones como las ocurridas entre el periodo 2010 – 2011, cuyos efectos repercutieron en pérdidas económicas para la región. Por tal motivo se realizó el análisis hidrológico de las crecientes históricas del río Cauca. La metodología se estructuró en tres etapas para identificar los factores hidrometeorológicos más influyentes: i) Descripción general de la cuenca para identificar las principales características; ii) Análisis de frecuencia de eventos máximos, aplicando funciones de distribución de probabilidad a las series de precipitaciones y caudales máximos diarios; y iii) Caracterización hidrológica de las crecientes posteriores a la construcción del embalse Salvajina (1988 – 2011). Como resultado, se identificó que uno de los factores más influyente en las crecientes, son las precipitaciones asociadas a la fase fría del fenómeno El Niño Oscilación del Sur (ENOS), La Niña; las cuales afectan significativamente el caudal del río y sus tributarios.

Palabras clave: *Análisis de frecuencia, eventos máximos, fenómeno ENOS, la Niña, río Cauca.*

Abstract
The Cauca River is the main surface water source in Valle del Cauca. In the past 25 years, it has registered important flows causing floods as the ones that occurred between 2010 and 2011, whose effects passed in economic losses for the region. The aim of this paper is to carry out a hydrological analysis of historical floods of the Cauca River. The methodology was structured in three stages to identify the most influential hydro-meteorological factors: i) General description of the basin to identify the main characteristics; (ii) Analysis of the frequency of maximum events, applying probability distribution functions to series of precipitation and maximum daily flows; and iii) The hydrological characterization of floods that occurred after the Salvajina dam was constructed (1988-2011). As a result, it was identified that the most influential factor causing floods is the precipitations associated with the cool phase of El Niño-Southern Oscillation (ENSO), La Niña; it significantly affects the river's flow volume, and its tributaries.

Keywords: *Analysis of the frequency, maximum events, ENSO phenomenon, La Niña, Cauca River.*

1. Introduction

Man has adapted to places with difficult environmental conditions, settling nearby river banks, and trying to take advantage of the fertility and abundance of these areas; it is for this reason that floods are linked to society's development (Carvajal, 2011). The Egyptian and Mesopotamian civilizations, and in America the Aztecs, Chibchans and Zenuans populated floodplains. It was possible due to their understanding of flooding and its benefits (Sedano *et al.*, 2013), they established a balance by using techniques for managing water. Currently, it is common to attribute disasters generated by floods to factors such as Climatic Variability (CV) and Climate Change (CC) which are caused by frequent precipitation anomalies (Vincent, 2007; Brown and Funk, 2008). It is difficult to establish a distinction between CV and CC in regions that are strongly influenced by CV in typical climate conditions, as it is the case in Colombia, where the hydro-climatology is influenced by the CV phenomenon, and the El Niño Southern Oscillation (ENSO). This phenomenon generates great changes in the global water and energy balance, causing strong hydro-climatic anomalies represented in its warm phase (La Niña), and cool phase (El Niño) (Poveda, 2004). Thus, some consequences are an increase in temperature in the first phase, and very intense precipitation events in the second phase.

The mechanisms that cause droughts during the warm phase of the ENSO phenomenon are described by Poveda (2004): the weakening of CHOCO jet, the reduction (not only in number but also in intensity) of tropical waves coming from the eastern tropical North Atlantic Ocean, the Inter-tropical Convergence Zone (ITCZ) displacement towards south-west of its normal position as a consequence of the Hadley's anomalous cell establishment on the American tropic, the alteration of the atmospheric humidity balance ─specially, in the lowest levels of the atmosphere─ and the precipitation reduction caused by a positive feedback. This last mechanism occurs when the soil moisture, the evapo-transpiration, and vegetation activity are reduced during El Niño; then, the recycled precipitation, which is estimated between 30-40 % in Colombia (Cuartas & Poveda, 2002; Poveda, 2004), diminishes. Evidence indicates that when the cool phase occurs, humidity coming into the region increases due to the CHOCO jet and east trade winds intensification. The recycled precipitation is caused by the soil-atmosphere interaction phenomena because the soil moisture, and evapo-transpiration play an important role during the extreme cool phase of ENSO, La Niña.

In addition to the complexity and the non-lineal behavior of ENSO interaction –Colombian hydro-climatology– the extreme phases are different in length and intensity, as well as their effects in each event. Not too long ago, the scientific paradigm assumed that El Niño and La Niña were opposite versions of the same phenomenon; however, each phenomenon is complex, and there are different types of extreme phases of the ENSO, as well as mechanisms that differentiate them; Cai et al (2014); (2015). They are based on the results of 21 models of the CMIP5 project that better reproduce the variations observed in both phenomena. They also highlight the fact of having characteristics and mechanisms to differentiate the factors causing the La Niña from the ones which cause the El Niño. Finally, they conclude that the occurrence of extreme La Niña events could duplicate because by projecting an increase in the temperature gradient between the maritime continent and the Pacific Ocean, the vertical temperature conditions on the ocean surface would improve, causing an increase in the frequency of extreme El Niño events, which in turn, favor subsequent developments of extreme La Niña events, (Cai et al, 2015).

In Colombia, effects associated with ENSO intensify because it is located close to the tropical Pacific Ocean, which is an influence zone of ocean-atmospheric phenomena. Almost 90% of natural disasters that occur in the country are caused by hydro-meteorological phenomena; the Valle del Cauca is one of the most affected regions because it is located near to the Pacific Ocean, and highly influenced by the ENSO phenomenon, (Carvajal & Marco, 2005). Nevertheless, although the ENSO phenomenon strongly influences the Colombian hydro-climatology, other phenomena such as the Pacific Ocean Decadal Oscillation, and the Oscillation of the North Atlantic, among others, also affect the complexity of the mechanisms that interact in the country's hydro-climatology (Poveda, 2004).

In the 1950s, the valley of the upper Cauca was considered to be a region with a great potential for developing due to its natural resources, fertile soil and abundant water bodies (Velasquez &Jimenez.

2004). However, the periodic and continuous floods caused by overflows of the Cauca River and its tributaries stopped the exploitation of these resources. According to Posada &Posada (1996), from the 395,000 shallow hectares of the geographic valley, floods affected nearly 84,000 ha/yearly, that is to say, 23% of the surface, affecting towns and villages, and causing numerous losses in different economic sectors. In order to diminish the flood areas, the CCV (Regional Autonomous Corporation of Valle del Cauca) created the Cauca River Regulation Project in 1985; among its most important construction works was the Salvajina dam. It was built for several purposes, and its main functions are to control floods, and dilute or clean the river's pollution. The dam can store 866 hm3, and is located northwest of the Department of Cauca, about 108kms upstream from Cali, which is the capital city of Valle del Cauca Department (Figure 1, left). Another aspect of the Regulation Project to diminish floods are the complementary works or protecting rings constructed with dykes in the Cauca river and its tributaries, interceptor channels, drainage channels, and pumping stations. Nevertheless, at present, most of these rings are incomplete or were constructed by nearby landowners without any technical proposed specifications; in other words, the Regulation Project of the Cauca River is incomplete.

Floods occurring in 2010-2011 in the department of Valle del Cauca led to a review of the land improvement model to control floods proposed by the CVC in the 70s. The project was enhanced by introducing new sustainability approaches, and different actions to recover the river's space; all this within a main plan framework for the integrated management of floods in the Cauca River corridor, called "Corridor Project for the Conservation and Sustainable Use of the Cauca River System" (http://www.cvc.gov.co/portal/index.php/es/inicio-corredor-rio-cauca). In this case, the hydrological

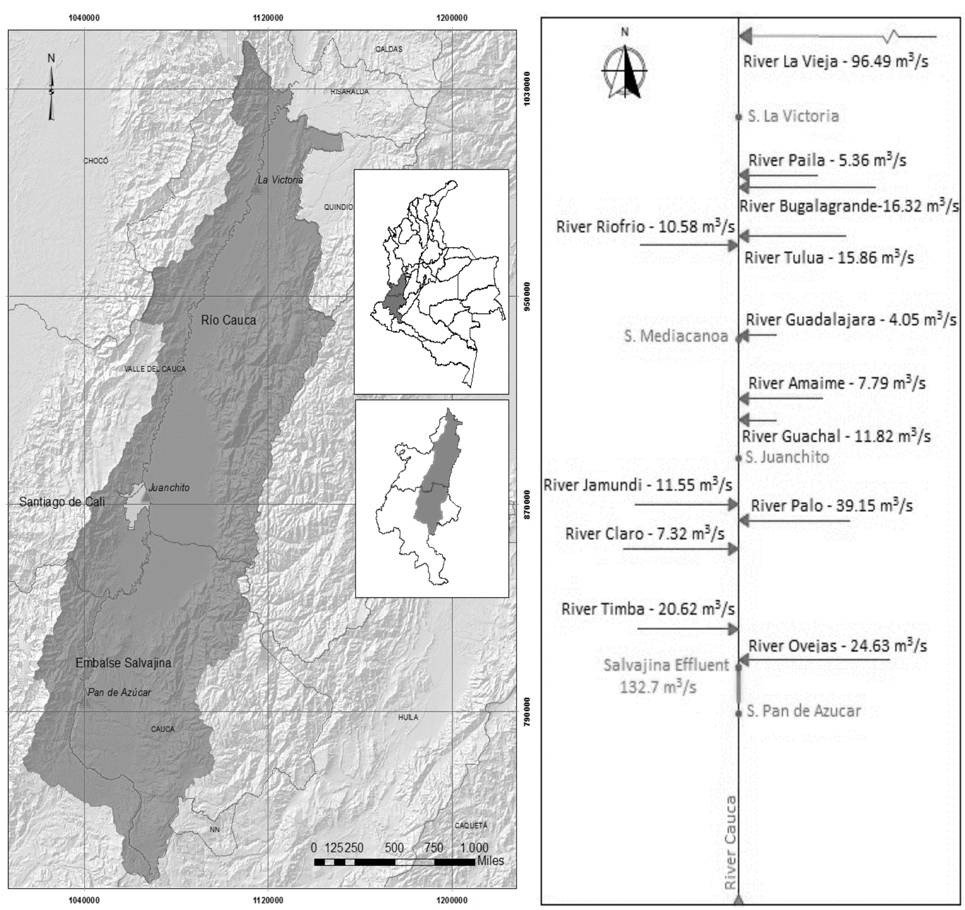

Figure 1. *Left, Location of the upper Cauca River basin. Right. General scheme of the upper Cauca River basin and its main tributaries.*

analysis became the main means to infer in the behavior of the hydro-meteorological variables, identifying the variations in the basin's hydrological processes. These analyses are important in the prediction of flood flows, and constitute a key point in risk management because they also provide tools for better planning the use and occupation of the territory (Gaume, et al., 2004; Zanon, et al., 2010). As a part of this project, the analysis of the hydro-meteorological factors that have caused the historical floods of the Cauca River is carried out in this paper.

2. Methodology

A general hydrologic characterization of the Cauca River upper basin was carried out in relation to its precipitation, the river's flow behavior in the four strategic points of the hydro-metric stations: Pan de Azúcar, Juanchito, Mediacanoa, and La Victoria (Figure 1, left), and to its main tributary rivers as well. Also, a frequency analysis (FA) of the maximum events of daily precipitation registered in 108 stations located in the basin, and the maximum daily flows registered in the same hydrometric stations was performed.

In the FA, the effect of the Salvajina dam in the hydrologic regime, and in the maximum daily flows series was considered. In the case of Juanchito station, the post-Salvajina period from 1985 to 2011 was analyzed. In Mediacanoa and La Victoria, where the regulation effect is not meaningful, the historical registration from 1965 to 2011 was used. Maximum annual series were used because they guarantee more independence in the data, when compared to the exceedance series, according to Chow et al. (1994), as the registration period increases, the results of both series converge. The functions of Gumbel distribution, which is widely used for analyzing maximum events in the region, the Log-Normal distribution that reduces the asymmetry in the extreme value series, and the Log-Pearson Type III distribution that gives good results in flow peak data were evaluated. The function selection that represented the best statistical adjustment was carried out applying graphic proofs by using Scatterplot Correlation Coefficient (SCC), and the Standard Error of Adjustment (SEA).

The hydrologic analysis was carried out for the flows occurred in the post-Salvajina period (1985-2011), taking into account the dam effect. For the characterization of historical floods, the Pan de Azucar, Juanchito, Mediacanoa, and La Victoria stations were used as referents, identifying flood windows periods where the river's daily flow exceeded the 60% of the mean multiannual value. With the Oceanic Niño Index (ONI), used by the National Oceanic and Atmospheric Administration (NOAA), the La Niña phase impact on a flood formation was identified. The information was classified during two semesters, from the bio-modality of the hydrologic regime in the basin, and associating the return periods to the maximum daily flows registered in the selected stations. Using the water balance, the maximum daily flow percentage provided by each tributary to the Cauca River at the maximum peak in each flood was determined. Afterwards, the maximum consecutive precipitations accumulated in 1.3 and 6 days prior to the maximum flow event were analyzed, and the precipitation space behavior was described during the mentioned events, identifying the zones with rains above 60 mm per day, 90 mm per three days, and 120 mm per six days.

Table 1. *The characteristic aspects of the hydrometric stations.*

Station	Height (mals)	Cumulative drainage área (km^2)	% Cumulative drainage area	River length (km)	Annual average flow (m^3/s)		Tt* (days)
					Before Salvajina	After Salvajina	
Pan de Azúcar	1,156	2,658	16	126	99	99	1
Salvajina	1,155	3,652	22	157	-	-	-
Juanchito	956	8,556	53	296	289	290	1
Mediacanoa	942	12,118	74	378	336	320	2
La Victoria	911	16,296	100	527	411	385	4

*Source: Sandoval and Ramirez (2007) *transit time (tt)*

3. Results and discussion

3.1. General hydrologic characterization of the studied zone

The Cauca River headwater is in the Colombian Andean Mountain Range, flowing northwards between the Western and Central Cordilleras in the Cauca department, to its mouth at the Magdalena River. The upper Cauca, which is 578 km long, corresponds to the 48% of its total length (Figure1, Right), and it has a total area of 18,000 km2. The river's elevations go from 900 to 4,000 meters above sea level. It has 39 tributaries which increase up to three times the average flow of the river from the Salvajina dam (152 m3/s approx.), until it leaves the department of Valle del Cauca (568 m3/s approx.), (Sandoval and Ramirez, 2007). Table 1 shows some basin aspects related to each hydrometric station drainage area; the transit time (tt) characteristics were obtained from the place the river leaves the Salvajina dam.

Factors affecting the time-space distribution of the basin precipitation are the result of the general pattern of the atmospheric circulation, the relief of the Western and Central Cordilleras, the deep convection, the distance to the Pacific Ocean, and vegetation. Another factor is the equatorial lulls or inter-tropical convergence zone (Poveda, 2004; Cuartas & Poveda, 2002; Rueda & Poveda, 2006). Additionally, in the Pacific region of the department of Valle del Cauca, hydro-climatologic events are influenced by the time-space variability of the CHOCO jet; Poveda (1998) refers to them as trans-equatorial winds, which blow over the Pacific Ocean acquiring a path from west to east into the country as a surface current. Especially in the Pacific region, there is a strong correlation between moisture advection by the CHOCO jet and the different phases of ENSO, where the first weakens during El Niño, and intensifies during La Niña, causing abnormalities in the two hydrological phases (Rueda & Poveda, 2006).

The basin is strongly affected by the ENSO phenomenon in the Colombian western climatic variability, the hydro-meteorology presents a bimodal regime of rainy periods: in March-April-May, and September-October-November; and periods of less precipitation during December-January-February, and June-July-August (Figure 2, left). This occurs as a result of the double step or migration of the Inter-tropical Convergence Zone (ITCZ), which is characterized by low surface atmospheric pressures, the rise of moist winds and high cloudiness. In the wet period, the second season is the rainiest with precipitations above 200 mm/month. The annual average precipitation in the area varies from 1,290 mm and 2,280 mm per year; and according to Escobar, et al (2006), it increases proportionally to the altitude in the cordilleras' slopes. In general, the western slope of the Central Cordillera has the highest precipitation rate in the region, which is demonstrated by the number of tributaries in the right-hand bank of the Cauca River (See Figure 1, right). This can be explained as a consequence of the cold moist air masses path coming from the CHOCO jet, ascending along the western slope of the West Cordillera, and converging with the eastern trade winds, generating cumulonimbus clouds. The Western Cordillera air masses go along its eastern slope as katabatic winds toward the valley plains. There, they descend and heat humidity to the western slope of the Central Cordillera, where, according to Mesa, et al (1997), rain, caused from moist air coming toward the Cordillera, occurs mainly in the slopes and not in the valley bottom which is drier because it is narrower and higher. It should be noted that the air masses, coming from East of the valley and at high-altitude (above 5,000 m), produce rains when interacting with the cumulonimbus, which have a wide vertical development fostered by the mountain ranges, and also provide humidity.

As a consequence to the precipitation bimodality, the Cauca River flow has two cycles of higher and lower flowing (Figure 2, right). This behavior is more evident in the stations located downstream Salvajina. The main flooding tributaries in the upper Cauca are: La Vieja (2,870 km^2), Palo (922.01 km^2), Ovejas (812.39 km^2), Tuluá (779.50 km^2), Bugalagrande (669.9 km^2), and Timba rivers (512.98 km^2); however, Claro, Jamundí, and Guadalajara rivers are also important because they are in the areas with the highest specific maximum flooding 280, 245, and 187 $l/s/km^2$, respectively. The tributaries present annual average floods ranging from 4.05 m^3/s (Guadalajara River) to 96.5 m^3/s (La Vieja river) draining basins with high slopes that determine its torrential nature.

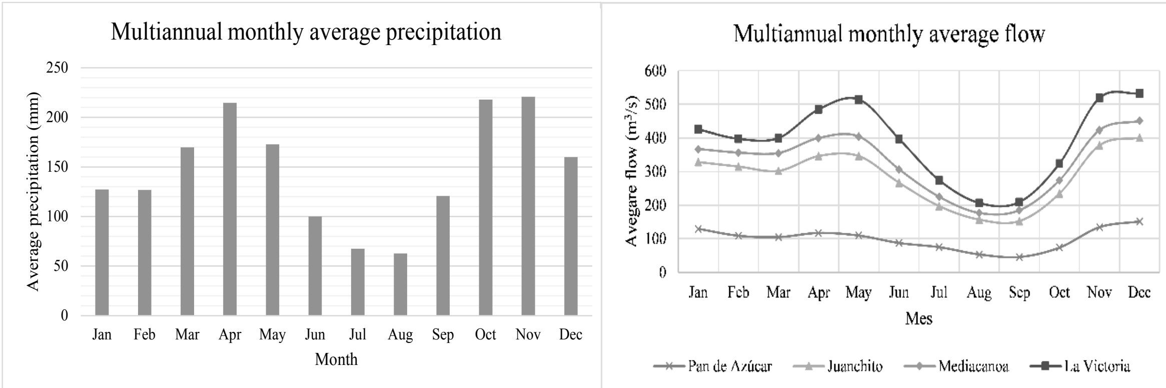

Figure 2. *Left: multiannual monthly average precipitation in the upper basin of the Cauca River, 1965 – 2011 period. Right: multiannual monthly average flow of the Cauca River, 1946 - 2012 period.*

In the CC context, some studies demonstrate that the basin precipitations have negative and positive trends with spatial not-defined distribution patterns (Ochoa & Poveda, 2008; Carmona & Poveda, 2011), identifying signals of a precipitation increase in the north and central parts of the department, and on the eastern flank of the West Cordillera, while decreasing trends are concentrated in the south region and the floodplain of the basin (Puertas et al, 2011; Cardona et al, 2014). In relation to the flow rate of the Cauca River, the trend of the multi-annual maximum values measured at the La Victoria station (Figure 3) agree with several studies, including Carmona & Poveda's (2011). They have identified declining trends in the series of flow averages of the main rivers of Colombia due to the combination of the CC impacts, and the anthropic activities in the basin, such as deforestation, and changes in land use. As a result, these actions have strong implications on the hydrological cycle regulation, and have uncertain conditions in the future. It also demonstrates that many hydrology series in the country do not fulfill the conditions for independence and stationarity (Poveda & Alvarez, 2012; Poveda & Pineda, 2009).

3.2 Frequency Analysis (FA) of maximum daily events of precipitation and flow in the Cauca River

The FA for the maximum events in the basin precipitation found that in 68% of the series (108 in total), the Log-Pearson Type III distribution function represents the best adjustment, followed by the Log-Normal function with 19% of the series, and finally the Gumbel distribution with 14%. The values of maximum daily precipitation for different

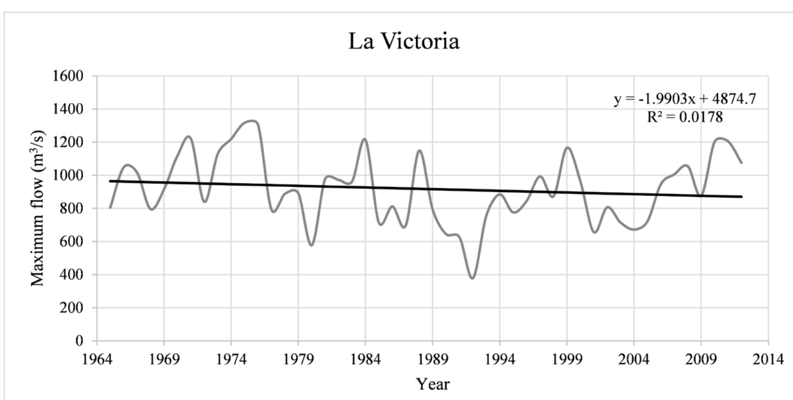

Figure 3. *Trend of multi-annual maximum flow rates of the Cauca River, La Victoria station*

return periods (Tr) calculated by Log-Pearson Type III tend to be lower than those calculated by other functions, which keep the trend as the Tr increases. In the AF of the maximum daily flow of the Cauca River, the incidence in the Salvajina dam regulation was taken into account only up to Juanchito station. It was because in the other hydro-metric stations (Mediacanoa, and La Victoria), the regulation effect was not significant, e.g. in the La Victoria station, the dam only regulates 22% of the drained area, while the remaining area receives contributions of the non-regulated tributaries which increase the river flow.

For this reason, the FA in the Juanchito station was carried out with the series of post- Salvajina (27 years) maximum flow rates, only considering the current hydrological regime of the Cauca River, without involving the deterministic component of the dam's controlled discharge. However, it is necessary to use other statistical models, adding factors in a detailed way, such as the influence of the dam's operation, the changes in land uses, and the climatic variability in the parameters characterizing the functions of the maximum flow distributions. It is important to emphasize that a complete series does not take stationarity into consideration because the current soil use differs from 60 years ago; nevertheless, including this series in a future analysis would link part of the climate variability of the area that is not regulated by the dam. The Juanchito station analysis is presented because its records are important for Cali. The Log-Pearson Type III function presented the minor SEA, and the SCC closest to 1, in comparison to other functions (Table 2); therefore, it was the best adjustment to the series of daily maximum flow in the four stations.

Table 2. *Adjustment values to the distribution functions, Juanchito station*

Function	Adjustment values	
	SCC	SEA
Gumbel	0.976	52.3
LogNormal	0.979	43.8
LogPearson III	**0.991**	**31.1**

As observed in Figure 4, the maximum daily flow rates estimated by the Log-Pearson Type III are lower than those estimated by other models for return periods exceeding 20 years, where the right-hand end of the curve tends to be limited to a threshold from Tr 700 years; while the other functions follow a trend to increase. This threshold can be related to the maximum flow rates that are sent on a basin according to its drainage area.

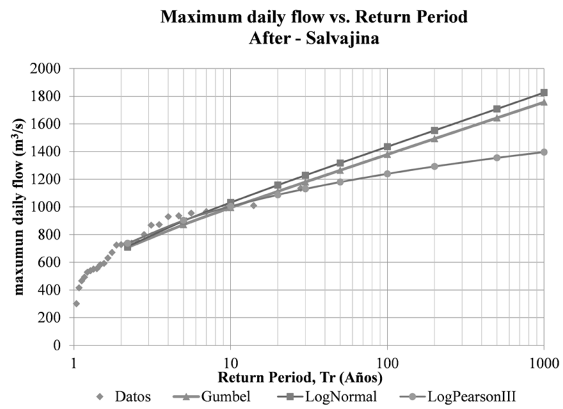

Figure 4. *Return period for each probability function, Juanchito station.*

The results obtained from the FA reinforces the need to consider the non-stationarity in the statistical modeling of maximum flow, which is represented in the non-linear distribution of the data. Poveda & Alvarez (2012) discussed the evidence of the stationarity lack in the hydrological series of Colombia, arguing that climate variability, land use changes, and deforestation influence the dynamic reflected in the records of hydrological variables. Therefore, by enhancing the estimates, drawing close to the system reality, the decision-making on the flooding risk will be less uncertain, and the protection structures more effective.

3.3 Hydrological characterization of the Cauca River's historical flows that gave rise to floods

We identified nine windows of representative flow between 1988 and 2011 (Table 3); with two flows per year in 1999, 2008 and 2011. 44% of the flows occurred in the first six months of the year, from January to June, and 56% from October to December; except for the flow that occurred in 1997, they are all associated to the La Niña phenomenon. These results are consistent with those presented by (Poveda, 2004; Poveda & Alvarez, 2012; Sedano et al, 2013), who identified and demonstrated the strong influence of ENSO on hydrology, especially on the flows of flooding in Colombia, and the studied area, whose behavior is reflected in its probability distribution.

Table 3. *Selected windows for the of historical flooding of the Cauca River.*

N°	Year	Windows flood		Year condition*
Flood first semester year				
1	2011	10/02/2011	05/06/2011	Niña
2	2008	01/01/2008	14/06/2008	Niña
3	1999	10/01/1999	19/05/1999	Niña
4	1997	17/01/1997	18/02/1997	Normal
Flood second semester year				
5	2011	10/11/2011	31/12/2011	Niña
6	2010	30/10/2010	12/01/2011	Niña
7	2008	16/11/2008	31/12/2008	Niña
8	1999	28/10/1999	31/12/1999	Niña
9	1988	09/11/1988	31/12/1988	Niña

** Based on information from the NOAA*

Considering the socio-economic and environmental impact that the Cauca River floods had in 2010-2011 in the Valle del Cauca department, which affected around 41,669 ha, a hydrological analysis of the November-December-2011 flood was carried out. The flood was strongly influenced by La Niña. During this flood, maximum flow rates were recorded with a frequency of 10, 20, 30 and 40 year occurrence, in La Victoria, Pan de Azucar, Mediacanoa, and Juanchito stations, respectively (Table 4). In the last station, the most representative, maximum flow was recorded during the Cauca River flood, when being compared to the peak flow rates registered in other stations, which did not exceeded a 10-year return period.

Table 4. *Maximum daily flow of the Cauca River for the flood in the window November-December, 2011.*

Station	Date maximum flow	Maximum flow (m^3/s)	Tr (Year)
Pan de Azúcar	07/12/2011	499	20
Juanchito	16/12/2011	1,135	30
Mediacanoa	17/12/2011	1,043	40
La Victoria	16/12/2011	1,205	10

The highest-percentage contribution to the maximum daily flow registered during this flooding in the Cauca River in the Savajina area, La Victoria (Figure 5), corresponds to its main tributaries with a 53% ratio, the Palo (13%), and Amaine (9%) rivers providing the highest discharges. It should be noted that in most historical floodings of the Cauca River, the Palo, Bugalagrande, Tulua, and La Paila rivers have had the highest discharges. Nevertheless, climate variability associated with the cool phase of ENSO generates frequent and strong precipitation anomalies such as in the case of La Niña in 2010-2011. Besides, not only the land use change but also the reduction of regulating vegetation coverage can cause, in a period

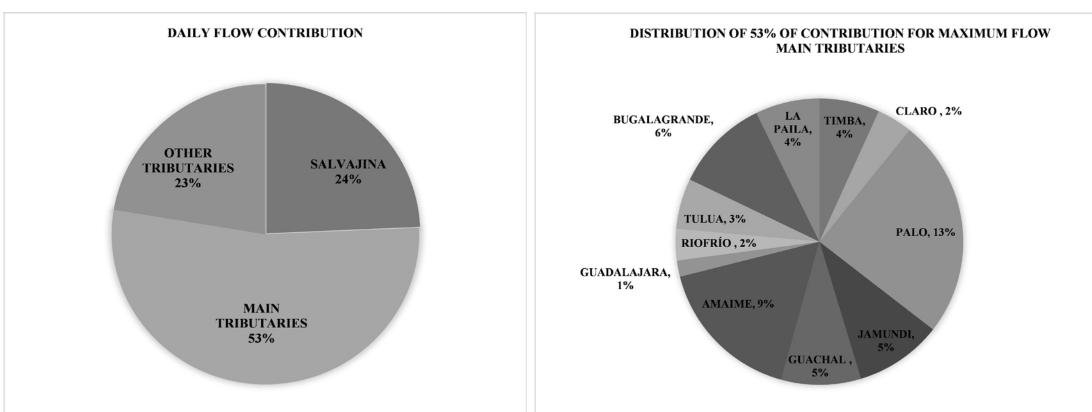

Figure 5. *Contribution Percentage by maximum daily flow in the Salvajina area -La Victoria*

of time, modifications in the series of maximum flows. This leads to remarkable increases in the peak flow of the tributary rivers that did not represent a great contribution to the Cauca River in the past, as the Jamundí, Amaine and Guachal rivers. All this contributed greatly to the maximum flow rate registered in the Cauca River estimated at the Mediacanoa station for the analyzed flooding.

In regard to the maximum precipitations recorded in whole basin for this flood window period, during the rainiest day, precipitations above 60 mm in the Jamundí, Amaine and Guachal rivers' basins occurred with 102, 89 and 85 mm respectively. However, these records present Tr below 5 years, and it indicates that the amount of daily precipitations are not representative extreme events in the Cauca river flow

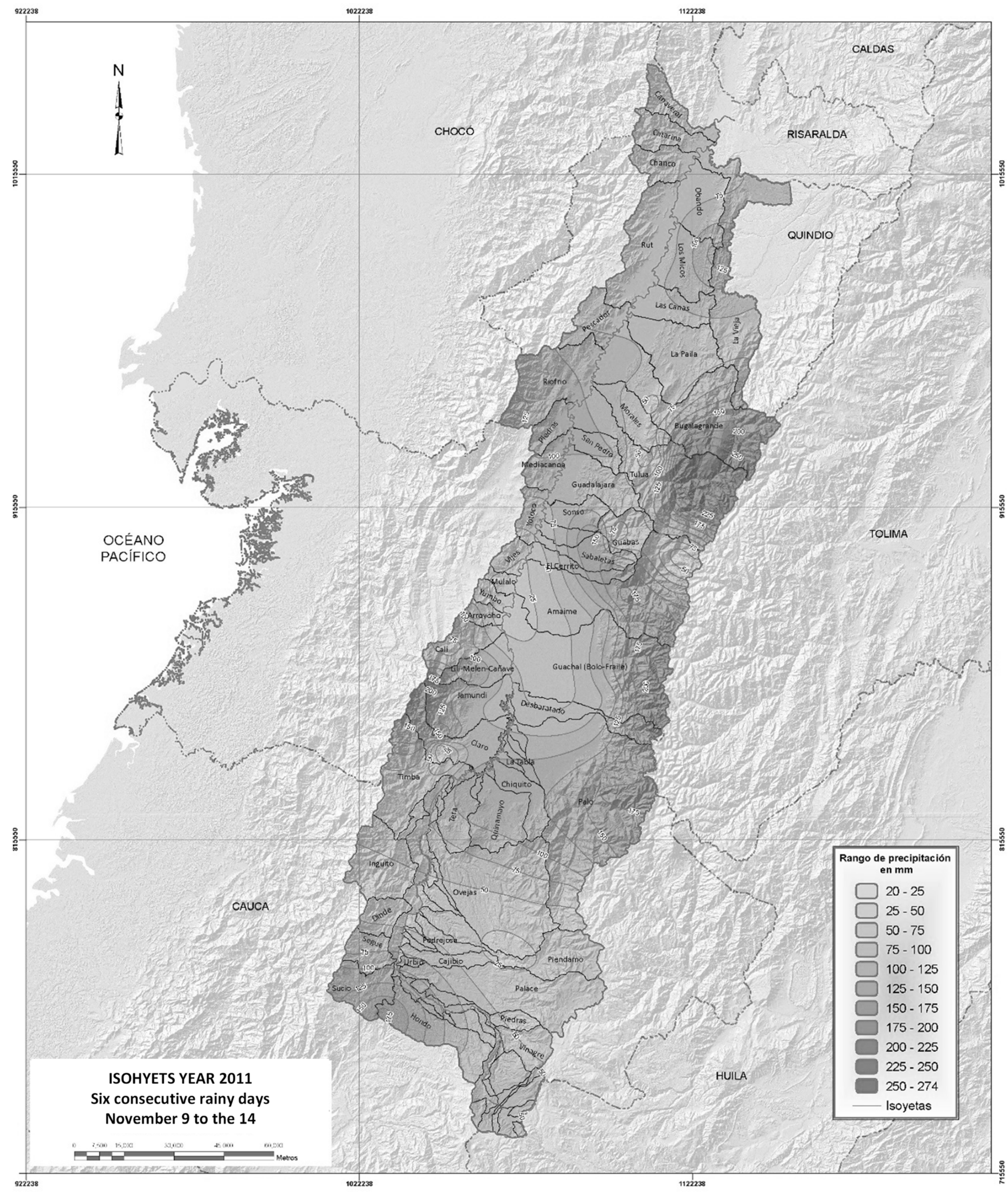

Figure 6. *The six rainiest day's isohyets in the flooding window, November-December 2011.*

increase. During the three consecutive rainiest days, highest precipitations were concentrated in the Jamundí, Guachal, Amaine, and Tulua rivers' basins, their records were between 147 and 194 mm. For the six consecutive rainiest days (Figure 6), the main precipitations were concentrated in Las Hermosas paramo (Tuluá and Bugalagrande rivers' basins), their precipitations reached values of 274 mm. Also, the rain corridor on the western slope of the Central Cordillera, which crosses the Guachal, Amaine, Desbaratado, and Palo basins presented records that ranged between 125 and 200 mm; while the Farallones National Park (Jamundí, Claro, and Cali basins) showed a nucleus up to 200 mm.

Almost all areas with the highest precipitation throughout the upper Cauca river basin coincide with the highest-specific-flow basins (Claro, Timba, Jamundí, and Guadalajara); although they do not make a great contribution to the Cauca River flooding, they are strategic areas for the planning and conservation of strategic ecosystems due to its high water production related to forest reserve areas such as the Farallones National Natural Park in Cali.

4. Conclusions

From the FA, it can be concluded that the commonly suggested functions and used for the maxima behavior study is the hydrological series of the Cauca River upper basin. Gumbel and Log-normal functions tend to estimate higher flow rates for return periods above 50 years, compared to the results with the function Log-Pearson Type III that presents the best adjustment in the hydrological series and tends to produce a constant value for high Tr. This is explained by the hypothesis which states that the maximum flow that can circulate through a watershed in function of its drainage area is associated to a superior limit, on the basis of the theory of the Probable Maximum Precipitation (PMP) and the Probable Maximum Flood (PMF).

The estimation of precipitation and maximum flood using distribution functions for the FA are fundamental considerations in the design, construction and optimal operation of the hydraulic structures. Nevertheless, the overestimation of maximum flood, a frequent problem in engineering, involves increases in the works cost. For this reason, in addition to the fine adjustment of the distribution function parameters to a series of records, it is important to perform a detailed and integrated analysis of other factors that affect the extreme flows in the basin (no estationarity), such as the influence of the dam operation, the land use change and climate variability associated mainly to the cool phase of ENSO.

The ENSO influence in its cool phase, La Niña, is one of the main factors in the generation of the historical flooding of the Cauca River; from the nine windows analyzed in the flooding that took place after constructing the Salvajina dam; eight of them have occurred under the influence of this phenomenon. The flooding that occurred between 2010 and 2011 had the greatest impact in relation to the flooded areas (41,669 ha) with flow rates associated to return periods of up to 40 years as recorded in the Mediacanoa station.

The maximum precipitation in 24 hours is important to study flooding in torrential river basins because they recorded few-hour concentration times. Nevertheless, in the case of the upper Cauca River, it is recommended to perform a FA for maximum precipitations between one and six consecutive days, considering that the Cauca River, i) presents transit times that exceed 4 or 5 days, and (ii) the precipitation analyzed during La Niña are characterized for being continuous and covering almost the entire study area.

The main nuclei of precipitation during the Cauca River flooding were located on the eastern flank of the West Cordillera in the Farallones National Natural Park in Cali, and on the western flank of the Central Cordillera in the Las Hermosas National Natural Park. This demonstrates the importance of the basin orography in the precipitation behavior. Further studies on several phenomena involved in the CV in the region are necessary to understand the relationship in the orography and climatology, and improve the monitoring of the hydrological and atmospheric dynamics of the tropical forests of the Andes, and relating the macroclimatic variables of the global atmospheric circulation

5. Acknowledgments

We thank the IREHISA research group, from Universidad del Valle, the Corporación Autónoma Regional of Valle del Cauca (CVC), and the Young Researchers and Innovators Program of COLCIENCIAS 2012 and 2013, for their contribution to develop the activity called "Hydrological Analysis of the historical Flooding of the Cauca River" which is part of the project "Construction of the conceptual model for restorating the corridor of conservation and sustainable use of the Cauca river system in its upper valley".

6. References

Brown, M. & Funk, C. (2008). Climate – Food security under climate change. *Science* 319 (5863), 580-581.

Cai, W., Borlace, S., Lengaigne, M., Rensch, P., Collins, M., Vecchi, G., Timmermann, A., Santoso, A., McPhaden, M., Wu, L., England, M., Wang, G., Guilyardi, E. & Jin, F. (2014). Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature climate change* 4, 111-116.

Cai, W., Wang, G., Santoso, A., McPhaden, Wu, L., Jin, F., Timmermann, A., Collins, M., Vecchi, G., Lengaigne, M., England, M., Dommenget, D., Takahashi. K. & Guilyardi, E. (2015). Increasing frequency of extreme La Niña events under greenhouse warming. *Nature climate change* 5, 132-137.

Cardona, F., Ávila, A., Carvajal, Y. & Jiménez, H. (2014). Tendencias en las series de precipitación en dos cuencas torrenciales andinas del Valle del Cauca (Colombia). *Tecnológicas* 17 (32), 85-95.

Carmona, A. & Poveda, G. (2011). *Detection of climate change and climate variability signals in Colombia and the Amazon river basin through empirical mode decomposition.* En Fall Meeting if the American Geophysical Union, San Francisco, USA.

Carvajal, Y. & Marco, J. (2005). Modelos multivariados de predicción de caudal mensual utilizando variables macroclimáticas. Caso de estudio Río Cauca. *Revista Ingeniería y competitividad* 7 (1), 18-32.

Carvajal, Y. (2011). Inundaciones en Colombia. ¿Estamos preparados para enfrentar la variabilidad y el cambio climático?. *Revista Memorias* 9 (16), 105-119.

Chow, V., Maidment, D. & Mays, L. (1994). *Hidrología Aplicada* (Trad. J. Saldarriaga). Bogotá, Colombia: McGraw Hill, Inc.

Cuartas, L. & Poveda, G. (2002). Balance atmosférico de humedad y estimación de la precipitación reciclada en Colombia según el Reanálisis NCEP/NCAR. *Meteorol. Colom.* 5, 49-57.

Escobar, S., Aristizabal, H., González, H., Sandoval, M. & Carvajal, Y. (2006). *Elaboración y actualización de isolíneas de precipitación, brillo solar, evaporación y temperatura mensual en el Valle de Cauca y la cuenca del alto Cauca.* En VII Congreso Colombiano de Meteorología, Bogotá, Colombia.

Gaume, E., Livet, M., Desbordes, M. & Villeneuve, P. (2004). Hydrological analysis of the rive Aude, France, flash flood on 12 and 13 November 1999. *Journal of Hydrology.* 286 (2004), 135-154.

Mesa, O., Poveda, G. & Carvajal, L. (1997). *Introducción al clima de Colombia*. Bogotá: Universidad Nacional de Colombia.

Ochoa, A. & Poveda, G. (2008). *Distribución espacial de señales de cambio climático en Colombia*. En XXIII Congreso Latinoamericano de Hidráulica, Cartagena de Indias, Colombia.

Posada, A. & Posada, J. (1966). *La CVC un reto al subdesarrollo y el tradicionalismo.* Bogotá: Ediciones Tercer Mundo.

Poveda, G. (1998). *Retroalimentación dinámica entre el ENSO y la hidrología de Colombia.* Tesis doctoral, Facultad de Minas, Universidad Nacional de Colombia, Medellín.

Poveda, G. (2004). La hidroclimatología de Colombia: una síntesis desde la escala inter-decadal hasta la escala diurna. *Rev. Acad. Colom. Cienc* 28 (107), 201-222.

Poveda, G. & Pineda, K. (2009). Reassessment of Colombia's tropical glaciers retreat rates: are they bound to disappear during the 2010-2020 decade? *Advance in Geosciences* 22, 107-116.

Poveda, G. & Álvarez, D. (2012). El colapso de la hipótesis de estacionariedad por cambio y variabilidad climática: implicaciones para el diseño hidrológico en ingeniería. *Revista de Ingeniería* (36), 65-76.

Puertas, O., Carvajal, Y. & Quintero, M. (2011). Estudio de tendencias de la precipitación mensual en la cuenca alta-media del río Cauca, Colombia. *Dyna* 78 (169), 112-120.

Rueda, O. & Poveda, G. (2006). Variabilidad espacial y temporal del chorro del "CHOCO" y su efecto en la hidroclimatología de la región del Pacífico colombiano. *Meteorol. Colom.* 10, 132-145.

Sandoval, C. & Ramírez, C. (2007). *El río Cauca en su valle alto: Un aporte al conocimiento de uno de los ríos más importantes de Colombia.* Cali: Universidad del Valle.

Sedano, K., Carvajal, Y., & Ávila, Á. (2013). Análisis de aspectos que incrementan el riesgo de inundaciones en Colombia. *Revista Luna Azul* (37), 219–238.

Velásquez, A. & Jiménez, N. (2004). *La gestión de riesgos en el ordenamiento territorial: inundaciones en Cali, la CVC y el fenómeno ENSO*. http://www.osso.org.co/docu/congresos/2004/A_Velasquez_Articulo_OSSO-UV.pdf.

Vincent, K. (2007). Uncertainty in adaptive capacity and the importance of scale. *Global Environ Change* 17 (1), 12-24.

Zanon, F., Borga, M., Zoccatelli, D., Marchi, L., Gaume, E., Bonnifait, L. & Delrieu, G. (2010). Hydrological analysis of a flash flood across a climatic and geologic gradient: The September 18, 2007 event in Western Slovenia. *Journal of Hydrology* 394 (1-2), 182-197.