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Sufficient analysis of an urban hydraulic work through the use of Hydraulic Modelling tools and Geographical Information Systems

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Abstract

The current climatic changes around the planet have caused the maximum events of the environmental phenomena to increase and to occur more frequently or at unusual times. The consequences of these changes are of great interest as a research topic for scholars of the subject and government entities. In this document, the results of the hydraulic modelling of two structures, made up of a canal and a bridge, located in the urban area of the city of Sincelejo, in northern Colombia, are presented. The modelling was carried out following the guidelines and recommendations of the Drainage Manual for Highways and the Technical Regulations of the Drinking Water and Basic Sanitation Sector (RAS) of Colombia. To carry out the modelling, field information such as the topography of the site, values of precipitation records measured by the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) was used; Similarly, GIS tools were used to obtain the geomorphological parameters of the basins; while the hydraulic modelling itself was carried out using the HEC-RAS model from the Hydrologic Engineering Centre. According to the modelling carried out for different return periods, it was possible to establish that the structures under study present a deficient behaviour in the event of extreme floods, for which the redesign of said works is recommended, in accordance with the current climatic conditions and expected future

Keywords: Precipitation, Return period, Design flow, Curve number, HEC-RAS, USC hydrograph, Floods, Climate change.

I. INTRODUCTION

Humanity has been involved in many changes in this century, some of them being very favourable, such as the great advances in technology; but others have been counterproductive, affecting and even putting people's lives, their property and the environment at risk. An example of the latter is the phenomenon known as Climate Change, which has become a central issue in the environmental field, and is currently one of the most worrying issues related to the alteration of the global climate system [1]. Climate change currently occupies the first places among the problems that affect humanity, ranking among the top positions in the ranking of social concerns, due to its direct impact on human relations and negative environmental effects [2]; therefore, it is a mandatory issue that concerns everyone responsible and is present in any government agenda.

The current reality has led governments and inhabitants around the world to face drastic changes in the climate, human activities being one of the factors that have favoured this phenomenon and what makes it a more difficult problem to face, because it requires changes related to human behaviour and people's way of life [3]. So it is not only a job that involves the academic community and governments, but it is the responsibility of all people to face the already imminent climate altercation worldwide.

Climate change is causing environmental degradation, bringing with it problems that are affecting all nations and economic levels, through floods, storms, heat waves, cold waves, hurricanes and other phenomena related to the environment, which before They did not appear as frequently, leading humanity to live in an increasingly complicated world [3] [4].

Studies on climate variability have shown that the climatic parameters have had a high variation in recent years, presenting values much higher than the annual historical maximums. Worldwide, floods are considered the most damaging and dangerous natural disaster [5] [6]. In the case of Colombia, floods are the natural phenomena that generate the highest number of affected families and destroyed homes per year [7]. At present, an increase in the intensity and magnitude of the precipitations causing these floods and sudden floods has been witnessed, giving greater importance to the determination of the risk due to floods.

One of the cases of interest is the study of hydrological models of hydrological basins and their variation in the face of climate change. Basins act as processes and response systems where surface runoff is the most obvious consequence, in addition to being responsible for catastrophes and natural disasters, and for numerous damages related to floods and floods [8], being of vital importance the treatment of hydrological basins with areas of influence in urbanized places, which have old drainage systems where many times the capacity of these structures is undersized, due to the fact that their useful life has already expired, or that they were conceived in times where the Weather conditions were not as extreme as they are today.

Hydrological modelling is a very useful tool for the study of floods, which has spread throughout the world and is widely used in developed countries. Based on these models, analyses and programs can be carried out to help minimize the impact of floods on communities at risk [9]. Hydrological models, like hydraulic ones, implemented in a computer, meet these expectations, forming a work path that increases the power of calculation operations [8] and yields results, giving information with a high degree of confidence for the decision making. A clear example of this are the models that are supported by Geographic Information Systems (GIS) and in the case of hydrological models, an excellent tool for modelling precipitation runoff systems is the HEC-RAS model of the Centre for Hydrological Engineering of the Army Corps of Engineers.

Carrying out this kind of modelling is not usually easy in many cases and requires time and financial resources, sometimes being difficult to finance for government, environmental or disaster mitigation entities. This document aims to model a main hydrological network located in the city of Sincelejo, in northern Colombia. The purpose of the study is to determine the hydraulic operation of two drainage works made up of a canal and a bridge, which are located in an important section along the route of the basin. The proposed methodology requires the combined use of different tools: vector and raster GIS, hydrological and hydraulic models, spreadsheets, plans and databases. The estimation of flood flows has been made on the basis of design storms with different return periods, using extreme event methodology. Once the maximum design flows have been obtained, the height of the water depth is calculated using the HEC-RAS hydraulic model (application for modelling and simulation of floods).

II. MATERIALS AND METHODS / EXPERIMENTAL DESIGN, MATERIALS AND METHODS

II.I Study area description

The city of Sincelejo, capital of the Department of Sucre, subregional centre of the Colombian Caribbean urban system, is located in the northeast of the country at 9º 18 ”north latitude, 75º. 23 ”latitude west of the Greenwich Meridian; It has a total extension of 28,504 hectares that represent 2.67% of the total area of the department, of which 92% corresponds to rural territory, with a height above sea level of 213 meters and is bordered to the south by the municipality of Sampués and with the Department of Córdoba; to the west with the Municipalities of Palmito and Tolú; to the north with the Municipalities of Tolú and Tolú Viejo and to the east with the Municipalities of Corozal and Morroa [10].

It has an area in which most of its territory is flat, it has a warm thermal floor like the one that corresponds to the extensive savannahs of the Caribbean plains. It has some important streams among which are the Bomba, Cacique, Culumuto, El Bajo, Moquen, Salado and a few more. The hydrographic network of Sincelejo is comprised of the micro-basins of the Grande de Corozal, Canoas, La muerte, Mocha and San Antonio streams. An important part of the Sincelejo streams correspond to seasonal runoff channels that only carry water after the downpours; while in other cases, these conduct permanent domestic wastewater, such as the Pintao, Columuto, La Mula, El Paso, Venecia, and Caimán streams, which belong to the micro-basin of the Grande Corozal stream [11].

II.II Material and methods

For the determination of the maximum braces of the channel of the Arroyo El Pintao of the city of Sincelejo and the verification of the Bridge that receives the same name, the methodologies provided in the Manual of Drainage of Roads of the National Institute of Roads of Colombia were used. The selected point of interest corresponds to the section located on Calle 32 between Carreras 10A and 11, which is a key place where the El Pintao stream, one of the main tributaries of the city, crosses the road. For the hydraulic verification of the analysed structures, the change in the section was taken into account, both in dimensions and in roughness properties of the channel through which runoff flows, changing from a channel lined with reinforced concrete to a channel on land. Additionally, the analysed structure crosses an important road in the city (Calle 32), where a bridge is located, which allows the intersection of the flow of water with the road.

The hydrological analysis starts from the delimitation of the area of interest: for the case under consideration, made up of the bridge called El Pintao and the channel adjacent to it, works that are located in the channel of the stream that receives the same name. The meteorological information was taken from the pluviometric station located in the city of Sincelejo, which has enough pluviometric records taken over several years. Based on this information, the design flows that were used in the modelling of the rain events were determined. Said flows must be associated with the probabilities of the occurrence of events arranged by the competent entities. Based on the previous procedure, the hydrological verification of the sections of the bridge and the existing canal was carried out, obtaining as a result the determination of the maximum ties in the works and the occurrence or not of floods during the design avenues.

To develop this work, the following methodology was followed:

- Information gathering
- Field work
- Basin classification
- Hydrological Study
- Interpretation of results

The Information Gathering consisted of searching, classifying, processing and analyzing the input information of the model that was freely available, as was the case of the meteorological and climatic data obtained from station 25025270 - University of Sucre, included in the interval from 1984 to 2015, compiled by the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM). Similarly, satellite images were obtained with Digital Elevation Models (DEMs), through the public site ASF Data Search Vertex. Geological information was obtained from Geology Plate No. 44 prepared by the Institute for Research and Geoscientific Information Mining, Environmental and Nuclear (INGEOMINAS).

The field work consisted of carrying out a detailed topography of the areas surrounding the bridge, in such a way that a topographic survey was carried out upstream of the bridge (area of the channel lined in concrete) and downstream of it (channel on land). With this information, the characteristics were obtained at the point of arrival of the flow, thus obtaining the longitudinal inlet and outlet slopes of the flow in areas surrounding the works, cross sections of the works (canal, bridge, road, ditches) and of the channel on land. The details of some elements that hinder the flow of water and are found within the channel were also obtained, as was the case of works for covering pipes and manholes.

The Basin Classification was carried out using GIS tools, so that the information from the DEM was imported into the ArcGIS program and based on its geospatial analysis tools, a delimitation of the perimeter of the basin of interest and the main channels and secondary waters that drain through the basin. Additionally, the basin parameters were obtained: area, perimeter, length of the main channel, maximum and minimum levels, average widths, average slope, among others, which allowed classifying the account and obtaining its hydrological properties. In this section, the classification of Land Use and vegetation cover was also carried out, very important parameters for the hydrological model, because they allow determining the coverage of the basin and, in turn, its drainage capacity. For this process, the ArcGIS program was used again.

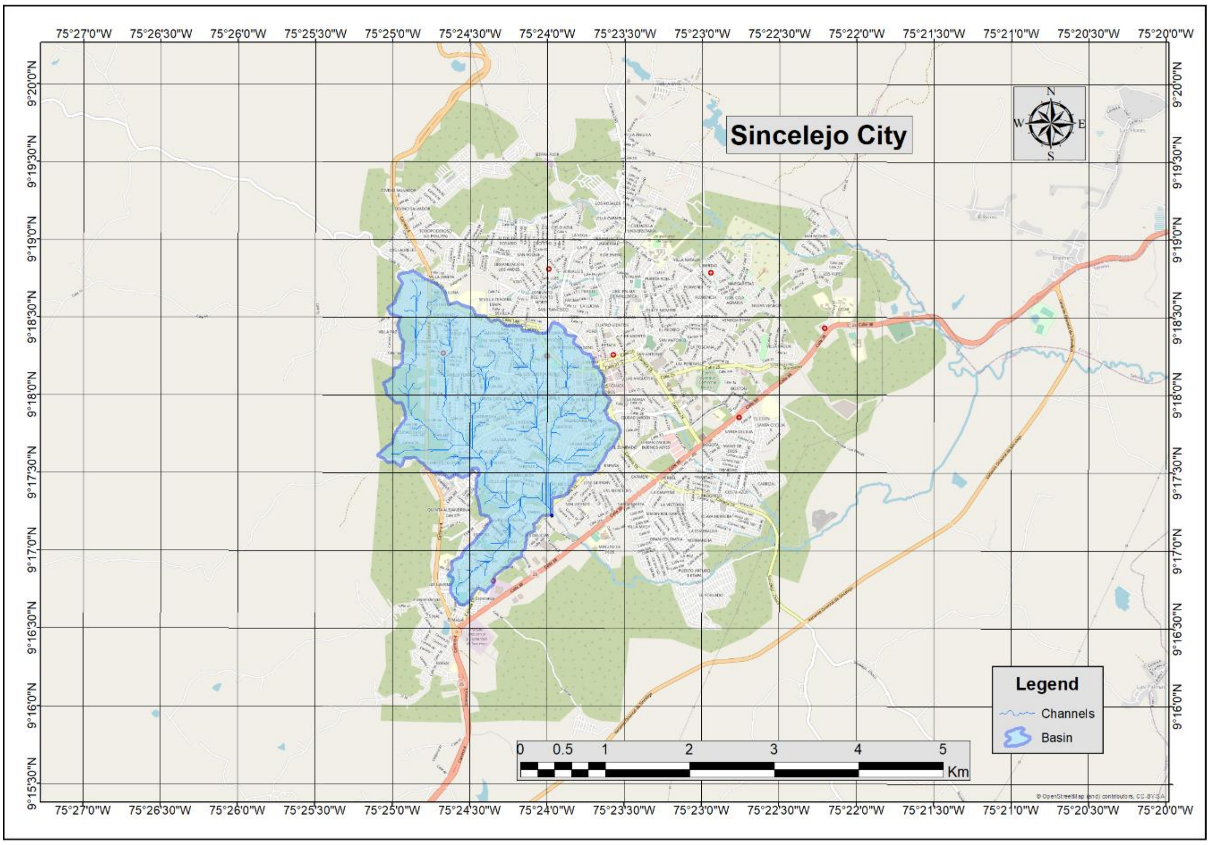

Fig. 1. Location of the hydrology network under study

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The Hydrological Model was carried out in several stages and using various tools. Initially, the maximum expected precipitation distribution was determined, through Gumbel's distribution theory, being able to find the extreme precipitation values for the different evaluated design periods. It is worth mentioning that this method is accepted in the Drainage Manual for highways - INVIAS and the selected return periods are based on the recommendations of the same document and the RAS [12] [13]. Gumbel's method works well for basins in the study area and consists of taking the maximum precipitation values and a certain return period, to obtain the design precipitation. This method is a probability function that is often used to obtain maximum values in large populations, like this:

$$P(x \leq xi) = e^{-e^{y}}$$

Where:

xi = Random variable

e = base of natural logarithms

y = deduced variable

From the moment method, the adjustment solution for this probability distribution is obtained, leaving:

$$X_f = \ddot{X} - S\frac{Y_n}{S_n}$$

Where:

X = Arithmetic average of the sample.
S = Standard or standard deviation of the sample data.
Yn, Sn = Mean and standard deviation of the reduced variable "y".
Xf = Parameters that depend on the number of years in the sample and on Yn, Sn, X and S.

The return period or occurrence interval is defined as the average time in years in which the peak flow of a flood is equal or exceeded once. This value is related to the probability of a probability distribution from:

$$T = \frac{1}{P(X \geq Xi)}$$

The Return periods chosen were taken from the values recommended in the INVIAS Drainage Manual, which correspond to 10, 20, 25, 50 and 100 years.

The second step consisted of calculating the design flows that were obtained from the Curve Number method and using the unit hydrograph of the United States Soil Conservation Service, SCS.

To apply the method, first the abstractions generated by the soil were calculated, assuming that the excess precipitation is equal to the total precipitation, minus the initial abstraction, minus the soil retention. This procedure is applicable for basins with areas greater than 2.5 km², and the effective precipitation is expressed as:

$$Pe = \frac{(P - 0.2S)^2}{P + 0.8\,S}$$

Where:

$$S = \frac{25400}{CN} - 254$$

CN = Number of Curve and depends on the hydrological condition, the type and cover of the soil.

For the Curve Number values, the type of hydrological soil, the use and treatment of the soil, the surface conditions of the land and the antecedent moisture condition in the soil were taken into account. After determining all these parameters based on the geographical area and characteristics of the basin, the Curve Number values for an Antecedent Humidity Condition II were obtained from the tables provided by INVIAS in its Drainage manual.

To determine the flow, the triangular unit hydrograph was used, a method that was developed by the U.S Soil Conservation Service and whose equation is:

$$Q_p = 0.208\frac{A}{t_p}$$

Where:

Qp = Peak flow of the unit hydrograph for 1 mm of effective precipitation, in cubic meters per second (m³ / s).
A = Drainage area of the hydrographic basin, in square kilometers (km²).
tp = Time to peak, in hours (h).

This procedure was carried out for each of the chosen Return Periods, obtaining the same number of design flows.

The third step consisted in carrying out the hydrological modelling itself, for which the Hec-Ras model was used, which is one of the most widely used models worldwide for hydraulic studies of uniform, one-dimensional and permanent flow. The software was developed by the U.S. Corp. of Engineers, Hydrological Engineering Center, HEC and is widely used today due to all the advantages it entails, such as flexibility in the creation of hydraulic scenarios, speed in calculations, easy handling and operation. The program is capable of modelling water surface profiles of mixed, subcritical and torrential flow regimes; likewise, it allows executing the mixed flow profiles, which includes and combines the results of the supercritical profile and the subcritical profile.

The interpretation of the results consisted in analysing the values of tie rods and the cases of flooding upstream and downstream of the bridge, along the concrete channel and on land, respectively. Based on this, modelling and adjustments could be made to the model, in such a way that the hydrological and environmental conditions were replicated in the most accurate way possible.

III. RESULTS AND DISCUSSIONS

The area and point of interest evaluated, presents a hydrological basin of important dimensions. The hydrological parameters of the same were obtained based on analysis carried out through the ArcGIS program, making use of Digital Elevation Models and topographic information taken in the field through the main stream channel of the basin. These hydrological parameters are shown in Table 1:

Through the parameters shown in Table 1, it can be expressed that the shape of the basin is slightly widened, the basin presents a pronounced relief, with a kind of elongation that is not very elongated and its compactness is defined as from oblong oval to oblong rectangular.

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Table 1. Geomorphological parameters of the Basin.

Parameters associated with the shape of the basin		
Área (A)	5653382 m²	
Perimeter (P)	13574 m	
Basin length (Lm)	3360m	
Basin width (Xm)	2824m	
Profile related parameters		
Maximum elevation of the channel (m)	255m	
Minimum elevation of the channel (m)	187m	
Main channel length (L)	4130 m	
Average slope of the channel (S)	0.0165 m/m	
Other basin parameters		
Horton Form Factor (Kf)	$K_f = \frac{A}{L^2}$	0.50
Elongation Ratio (Re)	$R_e = 1.128\frac{\sqrt{A}}{L}$	0.80
Elongation Index (Ia)	$I_a = \frac{L_m}{X_m}$	1.19
Compactness Coefficient (Kc)	$K_c = \frac{0,28 * P}{\sqrt{A}}$	1.60

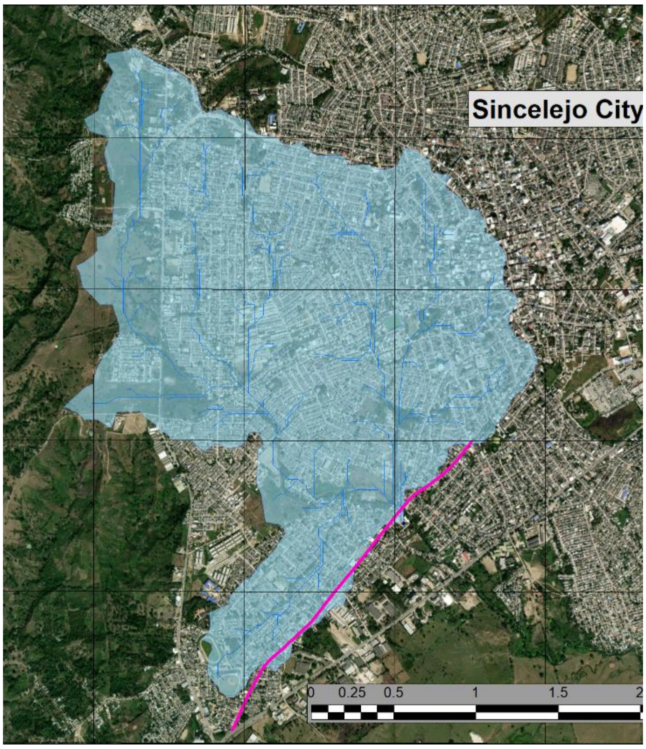

Fig. 2. Geomorphological parameters of the basin under study.

The design rainfall was obtained through the maximum rainfall measured at station 25025270 - University of Sucre, from a historical record of 31 years between 1984 and 2015.

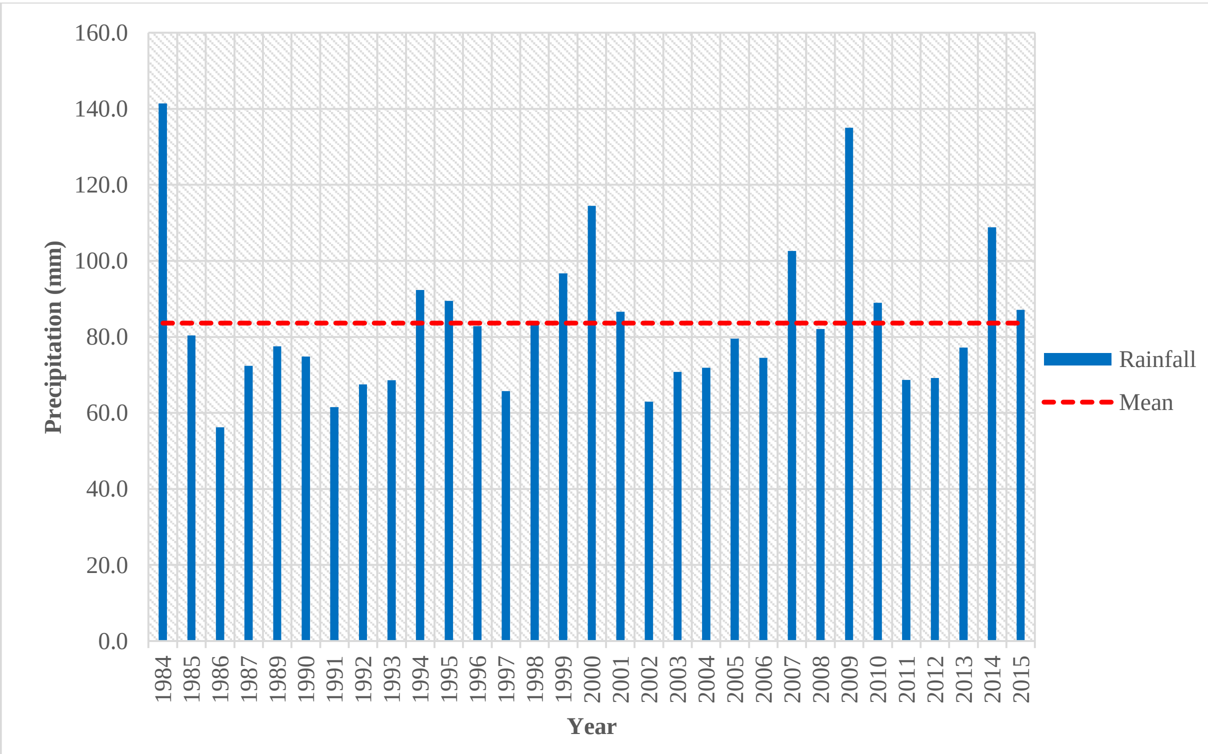

Fig. 3. Maximum annual precipitation for the IDEAM station.

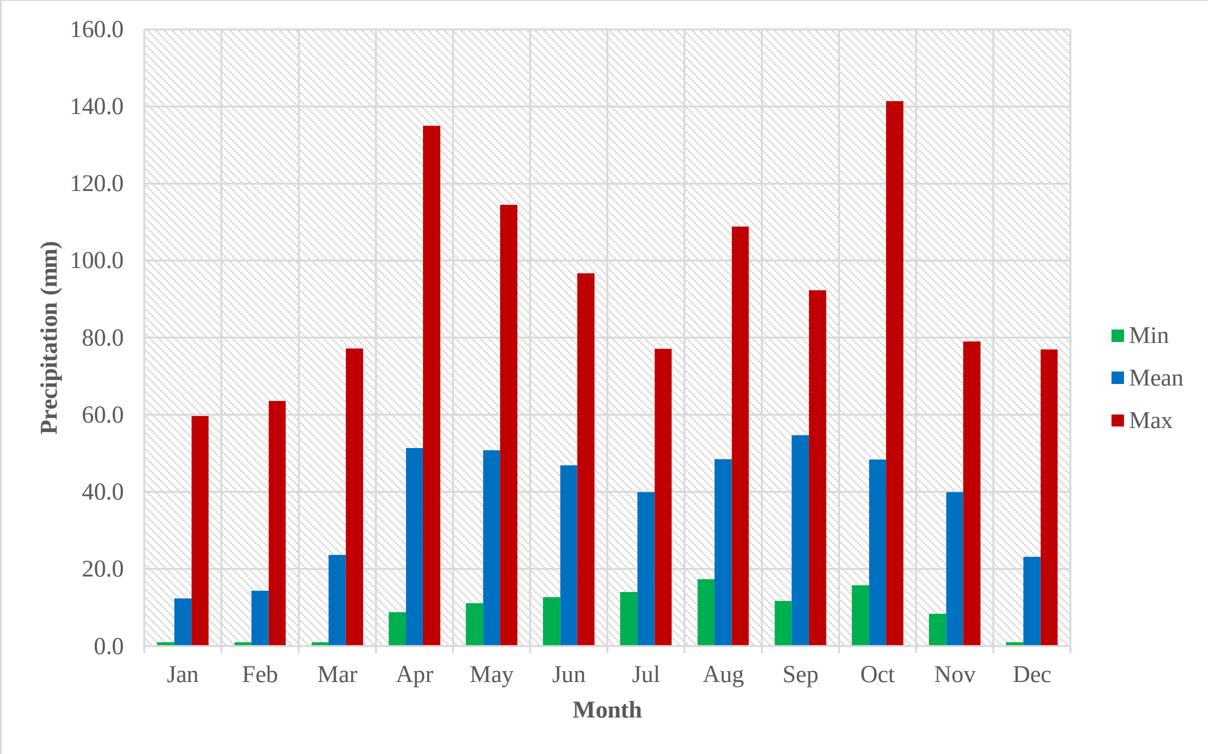

Fig. 4. Monthly precipitation for the IDEAM station.

In Fig. 3 the rainfall recorded for the different years in study. In this it can be observed that in five of the last 10 years of record, precipitation was above the annual average. Fig. 4 represents the minimum, average and maximum precipitation values of the rainfall recorded month by month for the 31 years of study. In this it can be seen that the months of April, May and June, as well as August, September and October, correspond to the ones with the highest rainfall, thus resulting in the most critical months for generating increases in flow and overflowing channels within the city.

The design precipitation values were calculated by the Curve Method and making use of the precipitations that were determined by the extreme values method. Table 2 shows a summary of maximum rainfall and design flows for each selected return period.

Table 2. Design Flows for the different return periods

Return Period (years)	Gumbel Extreme Values (mm)	Effective Precipitation (mm)	Design Flow (m^3/s)
10	98.01	95.41	**68.92**
20	108.67	106.06	**76.62**
25	112.05	109.44	**79.06**
50	122.46	119.85	**86.57**
100	132.80	130.19	**94.04**

Figures 5, 6, 7, 8 and 9 show a three-dimensional view of the channel of the El Pintao stream, near the Bridge under study. Additionally, the cross section of the upstream bridge is presented, where the water level for each return period can be observed.

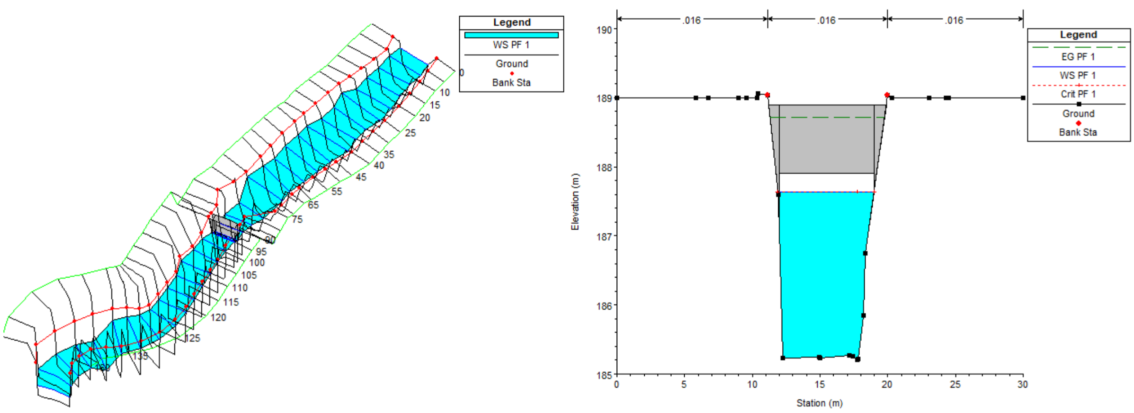

Fig. 5. Three-dimensional view of the channel and cross section of the bridge for design flow, Tr = 10 years.

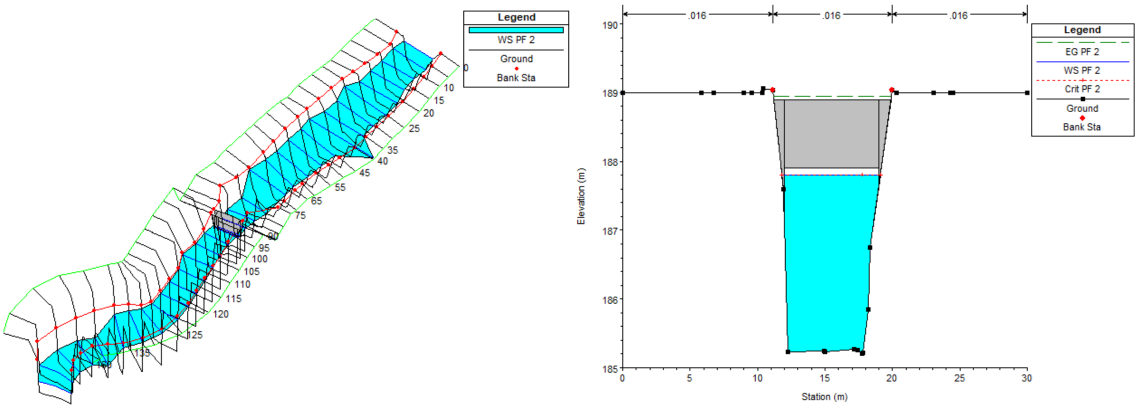

Fig. 6. Three-dimensional view of the channel and cross section of the bridge for design flow, Tr = 20 years.

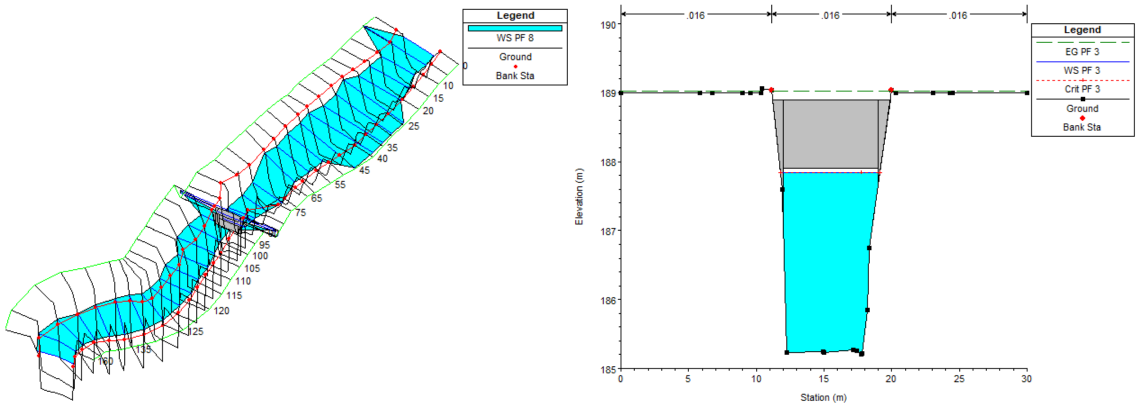

Fig. 7. Three-dimensional view of the channel and cross section of the bridge for design flow, Tr = 25 years.

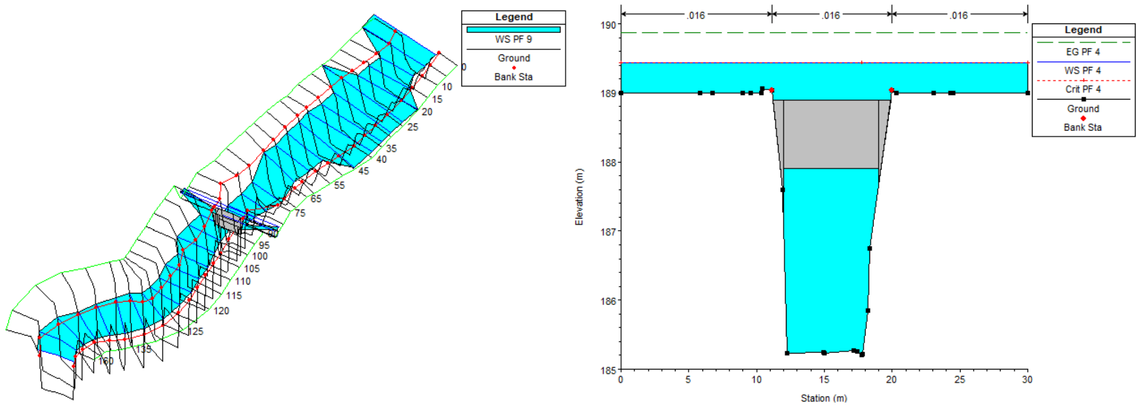

Fig. 8. Three-dimensional view of the channel and cross section of the bridge for design flow, Tr = 50 years.

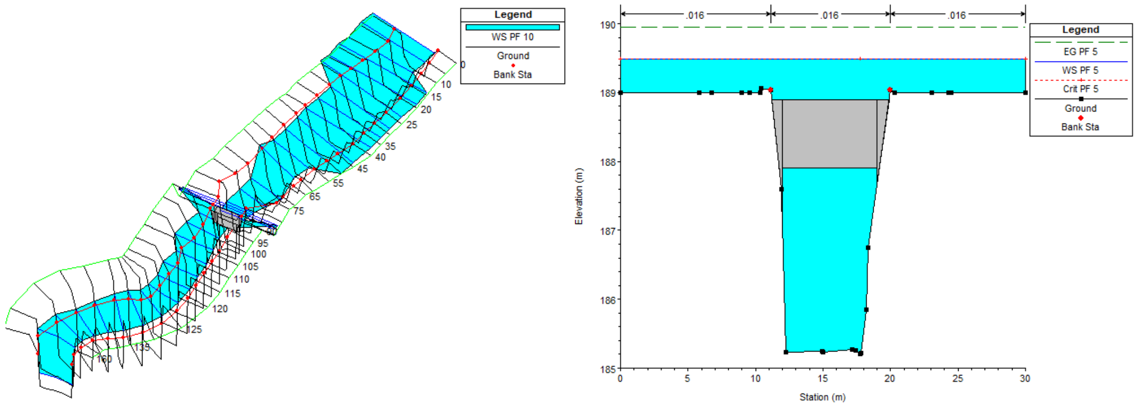

Fig. 9. Three-dimensional view of the channel and cross section of the bridge for design flow, Tr = 100 years.

Figures 5, 6, 7, 8 and 9 show the water levels for design rainfall corresponding to a Return Period of 10, 20, 25, 50 and 100 years, respectively. For the case of the canal, it is observed that for Tr = 10 and 20 years, it fulfills both upstream and downstream hydraulically; for Tr = 25 years, there is a small overflow in the channel, both upstream and downstream, being greater downstream; for Tr = 50 and 100 years, a significant flood is observed in the upstream part of the canal with significant obstructions near the hydraulic work (bridge). Additionally, downstream, floods occur almost all along the route, predominantly on the right bank of the stream.

On the other hand, with regard to the evaluated bridge, for Tr = 10, 20 and 25 years, there are tie rods very close to the lower level of the bridge girder, although they do not comply with the gauges recommended in current regulations. Now, for Tr = 50 and 100 years, the water depth exceeds the level of the bridge, presenting water levels of 32 and 36 cm, respectively, above the elevation of the existing road.

IV. CONCLUSIONS

According to the results obtained in the modeling carried out, the following can be concluded:

In the case of the canal, it was determined that for rains with return periods greater than 25 years, the channel will overflow upstream from the site where the bridge is located. Said channel sector is currently lined with concrete. Regarding the canal sector downstream from the bridge, which is on land, there will also be overflow for return periods greater than 25 years. However, if the design of the channel upstream of the bridge is improved, the occurrence of overflows downstream of the bridge could be prevented.

In the case of the bridge, for return periods of 10, 20 and 25 years, the tie reached is very close to the lower level of the bridge girders, however, this situation is inadmissible, because in none of the cases, the minimum gauge established in current regulations is met. Therefore, it is necessary to redesign the work, in such a way that it can support a design avenue corresponding to a return period of 50 years.

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