Physiographic and hydrological characterization in the Zula River basin, Jalisco, a challenge to the sustainability of water in the región

Caracterización fisiográfica e hidrológica en la cuenca del Río Zula, Jalisco, un desafío a la sustentabilidad del agua en la región

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Abstract

Water abundance along the Zula River has provided an important economic impulse to the agricultural and industrial sectors of tows and localities located within the river basin; therefore, such an impulse has caused greater water demands and to change from rural to urban the type of the watershed. The objective of this paper is to determine the physiographic and morphological characterization of the Zula River basin, to obtain peak flows based on 2 to 50 years return periods (Tr). This was achieved using a rainfall-runoff method in conjunction with probability and statistical models, all of which are indispensable tools for the proposal of flood protection embankments occurring along the tower part of the basin. The results obtained include the analysis and design of a synthetic hydrograph for the Zula river basin. As a final conclusion, the hydrological modelling responds accordingly to the equivalent speed of response and time of concentration aimed to minimize risks and disasters on the lower part of the basin, thus promoting the protection of human lives and material assets along the downstream.

Basin, Floods, Risks. Disasters

Resumen

La abundante agua del río Zula ha facilitado a pueblos y localidades de la cuenca el impulso económico en el sector agrícola e industrial principalmente el sector mueblero, como consecuencia ha ocasionado mayores demandas de agua, además de la transformación de la cuenca hidrográfica del tipo rural a una urbana. El objetivo de este trabajo es determinar la caracterización fisiográfica y morfológica de la cuenca del río Zula, así como la obtención de gastos picos para periodos de retorno Tr desde 2 hasta 50 años. Esto se logró utilizando la metodología del modelo lluvia-escurrimiento, así como modelos de probabilidad y estadística, herramientas indispensables para la propuesta de bordos de protección contra inundaciones que se presentan en la parte baja de la cuenca. Los resultados obtenidos fueron el cálculo y diseño del hidrograma sintético de la cuenca del río Zula, así como las subcuencas que la conforman Como conclusión la modelación hidrológica responde a la velocidad de respuesta y tiempo de concentración equivalentes para minimizar los riesgos y desastres en la parte baja de la cuenca, previniendo con ello la seguridad de vidas humanas y bienes materiales aguas abajo.

Cuenca, Inundaciones, Riesgos. Desastres

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Introduction

The Zula River and its tributaries suffer a severe pollution along theirs channels due to factors that have been accumulating over the last thirty years, among those agents we can mention the following: agricultural returns, creation of new housing developments, overexploitation of local aquifers, as well as direct wastewater discharges into the river (Lujan, 2016), these and other factors have substantially contributed to the ecocide of the Zula River.

Another problem found along the Zula River is the stagnation of its waters due to the small or null slope topographic configuration of the basin, thus, generating undesirable effects like the presence of large amounts of insects and unpleasant smells, especially during the dry season, some studies authored by scientists from the University of Guadalajara mention that the industrial pollution in the Zula River basin is originated by dairy wastes dumped directly into the municipal drainage, which flows into the river or study the area (Juárez, 2012).

It is well known that in most cases, liquid waste products with large quantities of milk whey, contain high concentrations of lactose (Lehninger, 2003) a disaccharide compound whose chemical name is β-D-galactosidase, also known as lactase which is widely used in the dairy industry for the hydrolysis of the lactose molecule into its corresponding derivatives: monosaccharides, glucose and galactose (Araujo, 2007); it is well documented that all these milk derivatives are discharged directly into the Zula River, as shown in the figure 1.

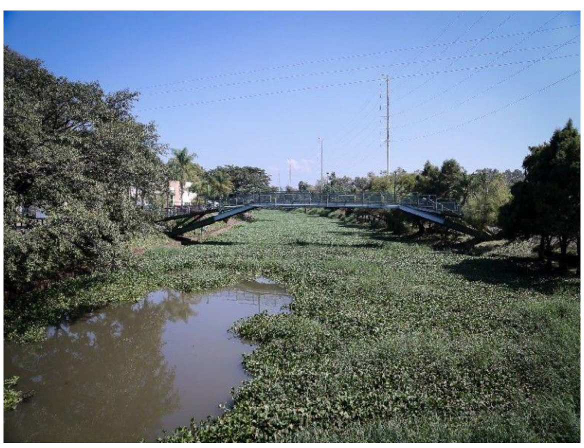

Figure 1 Hydrological deterioration of the Zula River
Source: www.decisiones.com.mx

Another serious problem are the annual floods registered periodically din the region. As a result of the heavy rains in the neighbouring municipality of Tototlan, severe overflows were registered along the Zula River, which affected homes located on the lower part of the basin.

Despite the local actions taken to abate extreme hydrometeorological phenomena, in support of the Global Climate Change (GCC) agenda, and according projections of floodable areas for 50-year based return periods, it has caused alterations to the hydrological cycle, there have been various climatic phenomena that have worsened during recent times: prolonged droughts, extreme rainfall intensities during shorter time intervals, and consequently, frequent and grater flooding events in the urban area of Ocotlan (Sánchez, 2011).

Therefore, the objectives of this project are to determine some hydrological parameters, such as the geomorphology of the basin and the sub-basins into which it is divided, and to identify flood plains and/or overflows occurring in the basin as a consequence rainfall runoff downstream, using *rainfall-runoff* model.

Project location

According to Mexico´s National Water Commission, the Zula River basin (CONAGUA, 2014) is located within the Administrative Hydrological Region VII Lerma-Santiago-Pacific, and the Hydrological Region 12 Lerma-Chapala which include portions of the hydrological basin of the Lerma River 7 and the hydrological basin of the Santiago River 1 *(ibid).*

The Zula River originates in the upper part in the municipality of Arandas and flows down into the Santiago River, which is formed by the numerous streams coming from all directions, its waters are not perennial runoff, and along its course there exist several waterbodies such as: Santa Isabel, El Rodeo, Agua, El Tule and Bombela reservoirs (State Water Commission, 2015).

The central geographic coordinates of the Zula River basin are 20° 20' 48" north latitude and 102° 46' 28" west longitude at an average altitude of 1750 meters above sea level, as shown in figure 2. The Ocotlan area, specifically the valley zone of the municipality is strongly influence by the Zula River, which flows through the region.

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Figure 2 Location on the Zula River basin
Source: www.earthgoogle.com

Figure 3 Overflows of the Zula River that caused flooding in the towns of the municipality of Ocotlan
Source: www.noticierostelevisa.com

Background

Rivers are one of the most visible phenomenal of the hydrological water cycle, for example: moisture that evaporates from the sea rises and is transported to the upper parts of the atmosphere where it condenses forming clouds, then, falls down later to earth in the form of liquid water (rain) or solid ice or snow (Aparicio, 2012).

Water bodies formed as part of the hydrological cycle make possible to provide to neighbouring populations with sufficient drinking water for their personal use and consumption. The availability of surface water in the Ocotlan area is almost exclusively intended for agricultural activities, with very a little portion of the remaining volume of liquid being provided for urban public urban use. Dams in the area, such La Guaracha, Xoconostle and San Vicente operate with a capacity equal to or less than 5 million m^3 (CEA, 2015).

Within the entire municipality of Ocotlan, surface water availability has been declared unavailable or having a water ban status. The only notable water source is the Chapala Lake. Wastewater sanitation is approximately 165 l/sec, precipitation averages 889 mm and evaporation averages 600 mm annually *(ibid).*

It is a prevailing knowledge to think that a forecast has to predict exactly how much rain will fall on a particular site in order to be able to make a proper decision. It is not possible to scientifically forecast weather variations due to the chaotic behaviour of rain, the challenge is precisely to use climatological information in an accurate way to properly communicate it to the population, so that data can be used as an element of risk management in the face of the GCC requirements and recommendations (Landa *et al,* 2009).

Historical background

The abundance of water in the Zula River basin facilitated the establishment of the Central Mexican Railroad segment between the Santiago River and Chapala Lake, a fact which impacted not only city of Ocotlan but also the surrounding towns across the region, promoting many economic activities such as agriculture, fishing, cattle raising and agriculture industries, among others (Montes de Oca, 1947).

These new forms of water management in the post-revolutionary period directly affected the waters users of the Zula River, especially farmers. The processes of reconstruction and nationalization of surface water required changes and new plans through which the civil engineers of the time were able to translate and adapt worldwide techniques of great complexity, based on a scientific and technological developments to be applied onto hydraulic infrastructure (Aboites-Aguilar, 2000).

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Industrial activities in the municipality of Ocotlan, Jalisco began in 1935 with the establishment of the Swiss company Nestle to settled to produce condensed milk, and in 1947 the North American company Celanese Mexicana, dedicated to the production of synthetic fibers, moved to the outskirts of Poncitlan (González, 1989). It was time when there was no an industrial development strategy for Jalisco and the activity expanded *"anarchically"* (McCulligh, 2020).

Later, during the Governor Juan Gil Preciado´s administration, the Guadalajara-La Barca highway was built, thus connecting the communities of Atequiza, Atotonilquillo, Poncitlan, Ocotlan, Jamay and La Barca with the purpose of promoting the industrial region of western Mexico.

During the government period of President Luis Echeverria (1970-1976) new economic incentives were introduced for the establishment of industries in less developed regions of the country (Cypher, 2013). Part of this decentralization process was the promotion of the then called Industrial Park of Jalisco (Lezama, 2004).

At first, it consisted of a 90 km long river stretch extending from the municipality of El Salto until the city of La Barca, Jalisco, an area which included the territory comprise between the Santiago River and the Guadalajara-La Barca highway, a region where electricity, railroad infrastructure and surface water services were available (Durán *et al,* 1999).

Water contamination along the Zula river is a severe problem, as shown with the following picture 4, from its source the river crosses the southern section of the downtown area of the municipal capital Arandas, where the ambient smell is imperceptible during rainy season, therefore, it is considered there a clean river; however, on the route between Arandas and the municipal capital of Atotonilco El Alto, the river passes by several tequila factories, receiving along its course wastewater and changing the water density and colour tone until it becomes a dense foamy gravy.

Figure 4 Pedestrian bridge over the Zula River, where you can perceive the foul smell of industrial wastewater discharged from the riverbanks from hundreds of meters away
Source: www.cronicajalisco.com

Along its course between Atotonilco el Alto and Tototlan, the river moves away to the south of both municipalities; there, the waters of the stream carry along added wastewater and rainwater from Tototlan and towards Ocotlan, "crossing this municipality, the river presents a foul smell in the afternoons between the towns of Zula, Labor Vieja and the municipal seat" (Zúrita and Hernández, 2002).

Methodology

The knowledge of the effects of a flood along a river allows us to obtain a reference line to take the most convenient preventive measures to implement safety protocols, in case of the presence of any extraordinary hydrological event that may cause flooding problems due to potential overflows coming from its channel and streams, we will have the necessary elements to determine the most appropriate solutions regarding a flood traffic, as well as the hydraulic behaviour of the Zula River.

The hydrological study is one the core activities of any kind, since it is the step that defines the amount of water that flows through the basin and the different sub-basins which are part of it, as well as the magnitude of the volumes that flow through the channels of the main streams is determined. For this purpose, the chosen methodology has been divided into three sections.

- Determination of the physiographic characteristics of the basin.

- Precipitation data analysis.

– Temporal distribution of rainwater for the basin.

Physiographic characterization of the basin

In regards of the physiographic characterization of a basin, a CivilCAD software was used in addition to the topographic information from Ocotlan, where the information layers and the vector data sets provided in shape format were of great help to detail all the characteristics of the study area.

To calculate the speed of runoff generated in the watershed at the lowest site of the basin or the time it takes for the lower basin runoff to arrive, it is necessary to use the average slope of the main channel using roughness coefficients of existing streams, the hydrological complexity of the watershed, as well as the physiographic and geomorphological characteristics of the selected basin (Quillatupa, 2016).

Basin area

It is defined as the horizontal projection of a surface delimited by the watershed divide. Surface of an area is considered the most important physiographic parameter of a basin. It is obtained by means of planimeters or by delimitation of topographic maps, and calculated with Computer-Aided Design (CAD) systems (Caro *et al*, 2017), the resulting value for the Zula River basin was 108.90 km².

The study basin boundary was extracted from the Ocotlan F13D77 INEGI´S topographic chart, using a scale 1:20000 for a better result, as well as to counterbalance the results obtained from Landsat image. Figure 5 shows the result based on the altitudinal surface, the magenta line indicates the area between contour lines and the orange colour shows the longitudinal perimeter of the watershed.

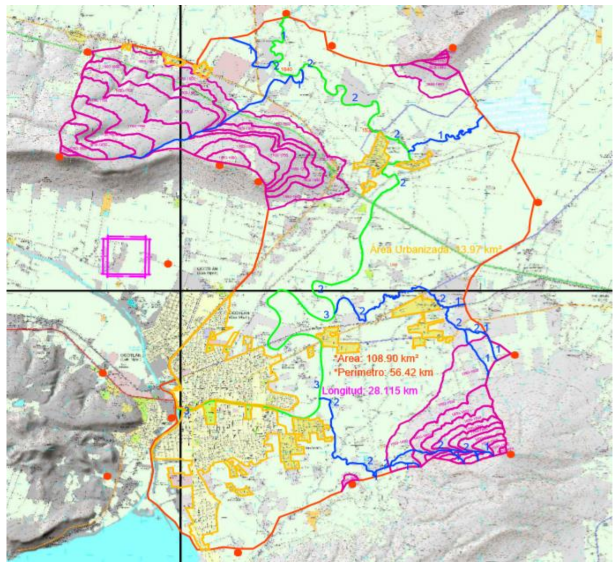

Figure 5 Topographic charts worked in AutoCAD highlighting urbanized area and hypsometry of the watershed
Source: National Institute of Statistics and Geography, INEGI

Main channel slope

The slope of the main channel is one of the most important indicators of the degree of response for a storm. (Aparicio, 2007). To obtain the average slope of the main channel, the Taylor-Schwarz method is used to calculate the average slope of the river similar to that of a uniform channel of equal length and travel time (Campos, 1998). This is defined by the following equation:

$$S = \left(\frac{\sum_1^n li}{\sum_1^n \frac{li}{\sqrt{Si}}} \right)^2 \quad (1)$$

$$S = \left(\frac{28115}{1069733.68} \right)^2 = 0.0006907$$

The following table and graph 1 show the lengths and slopes for each straight stretch, where runoffs were captured by the Zula River.

Rainfall-runoff model

Where there is no hydrometric instrumentation within or very close to the basin under study, the peak discharge can be determined by applying indirect methods, based on mathematical rainfall-runoff models (Lafragua, 2003), since they originate from numerous analyses in which the relationship between the amount of water runoff in a given sub-basin and the volumes actually stored in the basin was sought.

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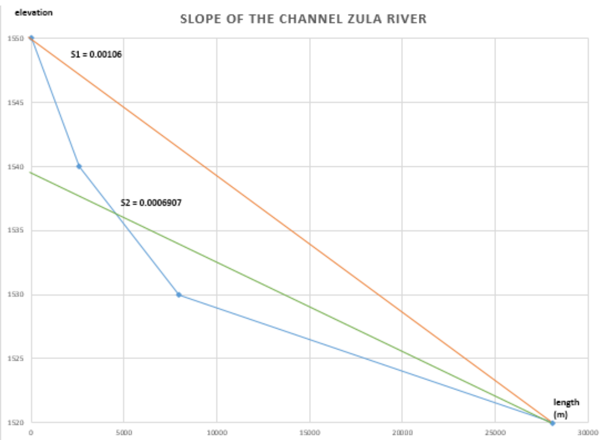
Elevation (masl)	Line between level curves	length (m)	slope	$\sqrt{Si}$	$\frac{li}{\sqrt{Si}}$
1520-1530	10	20111	0.0049	0.02222	901883.6
1530-1540	10	5432	0.0018	0.0429	126601.7
1540-1550	10	2572	0.0038	0.06235	41248.33
		28115			1069733

Table 1 Slope data by segment of the Zula River, Ocotlan, Jalisco. To obtain the constant equivalent slope by the Taylor-Schwarz method
Source: Own elaboration



Graphic 1 Slope of the Zula River Channel
Source: Own elaboration

As a first step for the creation of the hydrographs, it is necessary to consult data from the closest meteorological station closest to the study basin; in this case, El Fuerte climatological station is the only one near the basin that is still active, since Ocotlan station is out of operation. Within its monthly values, we find the summary of the last 60 years of precipitation (SMN, 2019). The method consists of determining a base precipitation height, which is associated with a duration of 1 hour and a return period of 10 years. From this, the specific precipitation height of the study basin is determined, for which the base precipitation is affected by three factors related to the duration of the storm, then the area of the basin and the return period are chosen to extrapolate the data.

Such factors were estimated after several analyses as shown in table 3, whose purpose was to establish a congruent relationship between the amount of precipitated water and the volumes of water runoff, its application is part of the effectiveness of the method so its values have been arranged in a table for practical purposes, as shown in table 2.

For duration Storm duration (hour)	storm Recommended factor	For area Area (km²)	basin Recommended factor	For period Return period (years)	return Recommended factor
0.50	0.79	1.00	1.00	2	0.67
1.00	1.00	10.00	0.98	5	0.88
2.00	1.20	20.00	0.96	10	1.00
8.00	1.48	50.00	0.92	25	1.15
24.00	1.50	100	0.88	50	1.25
		200	0.82	100	1.38
		500	0.70		

Table 2 Factors for adjusting the design rainfall
Source: Regional Water Management of the Valley of Mexico

The application of the method is very simple, but it is necessary to calculate some hydrological parameters of the basin, namely; length and slope of the main channel. On the other hand, it is also necessary to previously calculate some flood parameters, such as time of concentration (tc), excess duration time (de), lag time (tr), peak time (tp), base time (tb), unit peak flow (qp) and runoff coefficient (Ce).

As a first step to determine the peak flows, the concentration time is calculated using the Kirpich´s formula, which yields water travel time of the water from the upper area of (upstream) the basin down till the outlet point (downstream). Using a slope value of S = 0.0006907 which is exactly that of the land.

$$tc = 0.0003245 \left(\frac{lc}{S}\right)^{0.77} \quad (2)$$

$$tc = 0.0003245 \left(\frac{28115}{0.0006907}\right)^{0.77} = 14.24\ hr$$

The next step has involved the calculation of the design rainfall, associated with return periods of 2, 5, 10, 25, 50 and 100 years. Once the return periods have been assigned to the design rainfall, it is necessary to extrapolate numbers from the recorded maximum annual rainfall, since the return period designated for the analysis is rarely less than of the data. Once the design rainfall has been calculated for the proposed periods, the next activity consists of turn out the rainfall to runoff (Ce) and the unit peak flow (qp) based on the following models.

$$qp = \frac{0.555\ Ac}{tb} \quad (3)$$

$$qp = \frac{0.555 * 108.90}{32.94} = 1.836\ m^3/seg/m$$

$$Ce = \frac{Cnu * Anu}{Ac} + \frac{0.45 * Iu * Au}{Ac} \quad (4)$$

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$$Ce = \frac{0.15 * 94.93}{108.90} + \frac{0.45 * 0.80 * 13.97}{108.90} = 0.1769$$

The *Cnu* and *Iu* coefficients were determined based on previous studies conducted in the Zula River basin, determining conservative values of 0.15 and 0.80 respectively for the study area. The values of the *Anu* and *Au* areas were obtained by means of INEGI´S topographic charts of the region (F13D77, Ocotlan) at a scale 1:50000 and with the support of observations made during field trips.

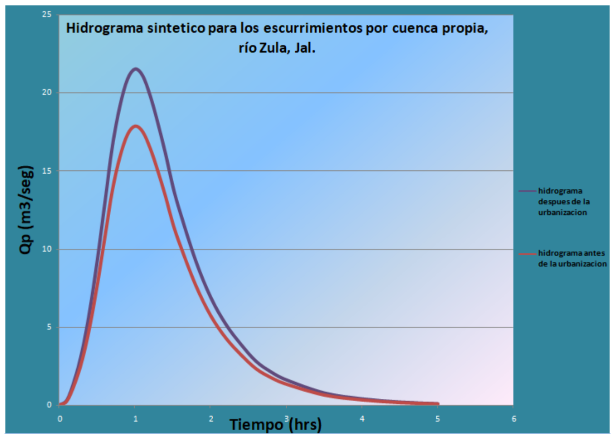
Results

Calculations with the average monthly mean precipitation along with its standard deviation will allow the creation of a storm design and flood table, the methodology of the *rainfall-runoff* model provides calculations of storm times and flows, as well as those coefficients related to the basin area. The results are the calculation and design of a hydrograph for the basin of the municipalities of Ocotlan and Tototlan, based on different return periods, as well as the sub-basins it is comprised of and where evidence of flooding has been present.

Based on the maximum rainfall recorded in 24 hours at the climatological station El Fuerte, the one-hour maximum rainfall and a return period of ten years, this was carried out by means of the quotient adjustment factor for storm duration of one hour (1.00) and the adjustment factor associated with the storm duration of twenty-four hours (1.50), as shown in table 3 and graph 2, which is the graphic representation of the synthetic hydrograph.

<table>
<tr><th colspan="6">Zula River basin, Ocotlan, Jalisco</th></tr>
<tr><td colspan="6">Maximun rainfall in 24 hrs for a return period Tr 10 years
Climatological station: El Fuerte</td></tr>
<tr><td colspan="6">Pmax (Dt, Tr) = Pmax (24 hours, 10 Years) = 74.71 mm</td></tr>
<tr><td colspan="6">Adjustment factor for duration of 1 hr = 1.00
Adjustment factor for 24 hr duration = 1.50
Pmax (Dt, Tr) = Pmax (1 hour, 10 years) = (1.00/1.50) * 74.71 = 49.81 mm</td></tr>
<tr><td colspan="6">Maximum precipitation for the storm duration and 10 years return period. Storm duration is considered to be equal to the time of concentration (tc)</td></tr>
<tr><td colspan="6">Storm duration = 14.5 hr
Adjustment factor for storm duration = 1.49
Pmax (Dt, Tr) = Pmax (2 hr, 10 years) = 1.49 * 49.81 = 74. 22 mm</td></tr>
<tr><td colspan="6">Maximum precipitation for the duration of the storm and 10 years return period associated with basin area</td></tr>
<tr><td colspan="6">Basin area adjustment factor = 0.875
Pmax (Dt, Tr, Ac) = Pmax (2 hr, 10 yr, 29.46 km²) = 0.875 * 74.22 = 64.92 mm</td></tr>
<tr><td rowspan="2">Return Period (years)</td><td rowspan="2">Adjustment factor for Tr</td><td rowspan="2">Design rainfall (mm)</td><td rowspan="2">Excess rainfall (mm)</td><td>Peak design</td><td>Flood discharge</td></tr>
<tr><td>Calculated m³/sec</td><td>rounder m³/sec</td></tr>
<tr><td>2</td><td>0.67</td><td>43.51</td><td>7.83</td><td>14.41</td><td>14.50</td></tr>
<tr><td>5</td><td>0.88</td><td>57.15</td><td>10.29</td><td>18.93</td><td>19.00</td></tr>
<tr><td>10</td><td>1.00</td><td>64.92</td><td>11.69</td><td>21.51</td><td>22.00</td></tr>
<tr><td>25</td><td>1.10</td><td>71.43</td><td>12.86</td><td>23.66</td><td>24.00</td></tr>
<tr><td>50</td><td>1.25</td><td>81.18</td><td>14.61</td><td>26.88</td><td>27.00</td></tr>
<tr><td>100</td><td>1.38</td><td>89.62</td><td>16.13</td><td>29.68</td><td>30.00</td></tr>
</table>

Table 2 Determination of maximum floods for different return periods Tr
Source: Own elaboration



Graphic 2 Synthetic Hydrograph on the basin Zula River
Source: Own elaboration

Conclusions

It is necessary to have an inventory of the natural resources in the Zula river basin, and to elaborate territorial maps corresponding to land use vegetation cover, hydrography, population density, etc. This information will be integrated by three subsystems: physical conditions, natural resources and urban settlement.

Knowledge of the soil humidity balance is important for activities such as agriculture, soil conservation and drainage, while the mapping characterization of the functional zones of the river basins yields useful technical information.

In the Zula river basin, the catchment-transport area covers 50% of its total area, which is where the watercourses, sediment materials and nutrient are found.

In regards of the natural aspects, a null slope is a predominant feature so that the response velocities are gentle and waterlogging occurs in the study area.

The peak flows for urbanization effects (before and after construction for the Zula River) were obtained based on the *rainfall-runoff* model, this methodology allowed to determine a base specific precipitation height which is associated with a storm duration of 1 hour and return period Tr based on 10 years, from this base specific design precipitation was determined, which is affected by three adjustment factors such as: duration of the storm, basin area and return period that were chosen to extrapolate the obtained data.

Recommendations

It is urgent to implement a bigger and better hydraulic infrastructure plan since only the urban area of the municipality has adequate sewer construction works, the afore mentioned will allow a more pleasant environment to detonate a totally sustainable and ecological tourism, in that order of ideas it is essential to work from an environmental engineering point of viuw in order to improve water quality.

The flora and fauna of the Zula River has been diminished and survives with difficulty, due to the ecocide in the region, fishing is not practiced because of the high degree of contamination, unfortunately one of the groups most affected have been the fishermen.

In terms of the national agenda, the priority construction of the Wastewater Treatment Plant (WTP) located in the town of San Juan Chico, as well as the work of dredging, removal of sludge and aquatic weeds as part of the Integral Plan for the Sanitation and Rescue of the Santiago River basin, in order not discharge wastewater to the Zula River.

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