

## Simulation of the flood zone for an extraordinary rainfall

## Simulación de la zona inundable ante una precipitación extraordinaria

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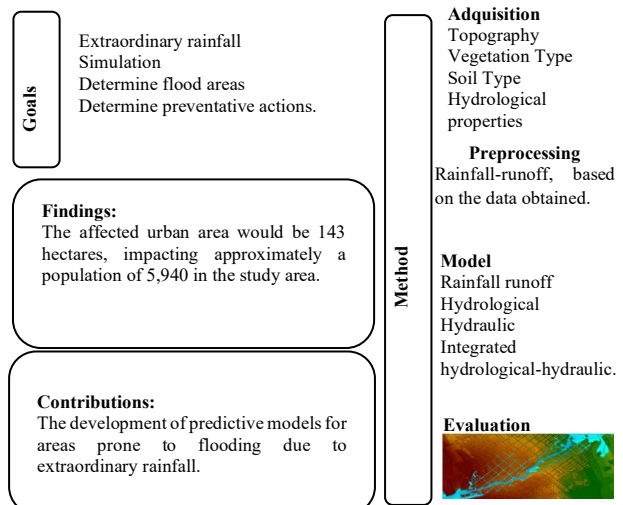
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## Abstract

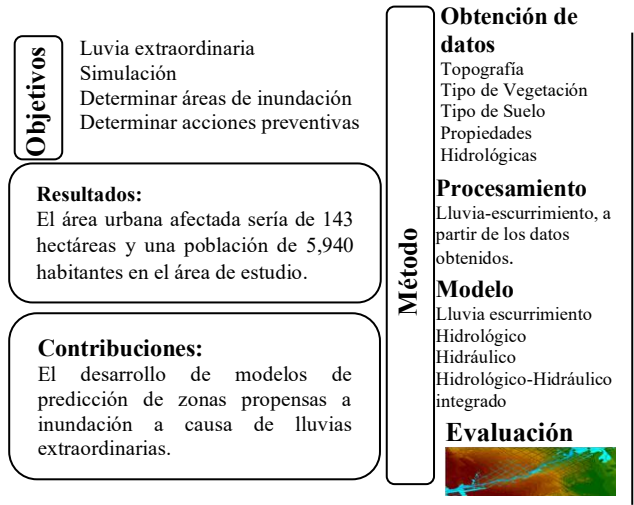
The presence of rainfall in a specific region can have a favorable impact by recharging aquifers and increasing storage volume in dams or reservoirs. However, when land use has changed from its natural behavior, it can cause flooding. The objective of this research was to simulate an extraordinary precipitation event in the Matamoros in a Mexican river by using an algorithm, which uses steady-flow water surface profiles modeled for gradually varied flow, the system can handle an entire channel network, a dendritic system, or a single river reach. The results indicate that for a design rainfall of 10,000 years return period the extraordinary flood will generate an elevation of 15 cm [2233.75 m.a.s.l.] over the crown [2233.6 m.a.s.l.], so under this scenario it is considered an account with hydrological risk. Also, it was obtained that for a controlled discharge for a return period of 10,000 years the affected urban area would be 143 hectares, impacting approximately a population of 5,940 in the study area.



## Maximum Rainfall, Flow, Flood, Simulation

## Resumen

La presencia de lluvia en una región específica puede tener un impacto favorable al recargar los acuíferos y aumentar el volumen de almacenamiento en presas o embalses. Sin embargo, cuando el uso del suelo ha cambiado de su comportamiento natural, puede causar inundaciones. El objetivo de esta investigación fue simular un evento de precipitación extraordinaria en el río Matamoros en un río mexicano mediante el uso de un algoritmo, que utiliza perfiles de superficie de agua de flujo constante modelados para flujo gradualmente variado. El sistema puede manejar una red completa de canales, un sistema dendrítico o un solo tramo del río. Los resultados indican que, para una precipitación de diseño de 10,000 años de período de retorno, la inundación extraordinaria generará una elevación de 15 cm [2233.75 m.s.n.m.] sobre la corona [2233.6 m.s.n.m.], por lo que bajo este escenario se considera una cuenta con riesgo hidrológico. Además, se obtuvo que para una descarga controlada para un período de retorno de 10,000 años el área urbana afectada sería de 143 hectáreas, impactando aproximadamente a una población de 5,940 habitantes en el área de estudio.



## Lluvia Máxima, Gasto, Inundación, Simulación

Area: Dissemination and universal access to science

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## Introduction

The presence of rainfall in a specific region can have a favorable impact, allowing aquifers to recharge and increasing the storage volume in dams or reservoirs. However, when land use has changed from its natural behavior, mainly due to the construction of urban infrastructure, coupled with the duration, intensity, and number of rainfall events, these events have implications and impacts at the local scale, primarily due to the effect of disasters related to runoff processes and subsequent flooding [Gochis et al. 2006].

Extreme events can occur at different scales, and the effects are generally more significant at the local scale. Therefore, in a small watershed associated with its geomorphological characteristics, there may be a greater impact on the population [Pineda et al. 2014; Xinyue Gu et al. 2025]. Likewise, if an additional component is added to these events, namely the discharge from the dam located upstream of the population, The stream that crosses the town has a free spillway designed for a flood with a 10,000-year return period, and the hydraulic capacity of the stream that crosses the town has been reduced.

Northwestern Mexico is generally semi-arid, with an annual rainfall pattern dominated by the warm convective season that interacts strongly with the regional topography and surrounding water bodies [Gochis et al. 2006]. At the same time, stream and river beds have been degraded mainly due to urbanization. The construction of bridges and dams has caused an imbalance in flow, mainly in seasonal streams, causing sedimentation problems in major waterways [Pineda et al. 2014].

These phenomena render the natural channel insufficient during extraordinary rainfall events. Extreme precipitation events require an understanding of the conditions under which they occur. This is important, as it could lead to the development of flood warning systems for flood risk management [Pineda et al. 2014].

Likewise, alternatives can be designed to manage the flow, either through the natural channel or by building new canals that channel water to neighboring basins before reaching the population, minimizing the floodable area.

The factors that generate extraordinary rainfall events in northwestern Mexico are linked to large-scale mechanisms, such as the North American Monsoon System [NAMS, also known as the Mexican Monsoon] [Cavazos et al., 2008].

In the highland region of Zacatecas state, significant rainfall occurs in the summer, especially in the months of July, August, and September. Each extraordinary event represents a potential flood hazard due to the region's topography and the degraded conditions of the streambeds.

Historically, the plains have suffered from flooding. The population initially formed the higher areas less susceptible to flooding, but population growth, lack of land use planning, deforestation in the upper reaches of the watersheds, and a false concept of security associated with dam construction has made populations and productive areas very vulnerable [Arreguín et al. 2012]. The potential damage caused by large runoff events has reached historic economic levels, estimated at nearly 42.1 billion pesos in 2022, and these events affected the state of Zacatecas. Therefore, it is important to study the risk associated with extreme weather events, and numerical modeling is a useful and easy-to-implement technique in watersheds with insufficient information. However, for flood modeling, a desirable property is the ability to integrate hydrometric data, flood extent, and high-resolution terrain maps for operational applications [Bates and De Roo 2000].

The issue of flood model validation has been analyzed for both 1D and 2D models [Horritt and Bates, 2002]. In data-poor catchments, 1D models such as the Hydrologic Engineering Centers River Analysis System [HECRAS] have been shown to generate sufficient flood impact information even for large-scale events [Horritt and Bates 2002]. Limitations may also arise from a lack of data resources for validating numerical weather prediction [NWP] models such as radar gauges and rain-bucket models [Bates and De Roo 2000]. However, evaluation of single-event models is limited in terms of the verifiability of results, but can inform responsible authorities to take preventive actions that prevent flood risk from materializing or, where appropriate, to take preventive measures to evacuate the floodplain and thus avoid human losses.

González-García, Cruz, González-Trinidad, Julián, Jénez-Ferreira, Hugo Enrique and Robles-Rovelo, Cruz Octavio. [2025]. Simulation of the flood zone for an extraordinary rainfall. *Journal of Technological Engineering*. 9[22]1-11: e2922111. <https://doi.org/10.35429/JTEN.2025.9.22.2.1.11>

The advantage of using NWP is its ability to generate high-resolution data grids at many scales [Xuan et al. 2009].

The objective of the research was to simulate an extraordinary precipitation event in the Matamoros stream of the municipality of Calera de Víctor Rosales, Zacatecas, Mexico through the HEC-RAS 5.0 program in order to detect flooding areas for prevention.

## Methodology

### Area of interest

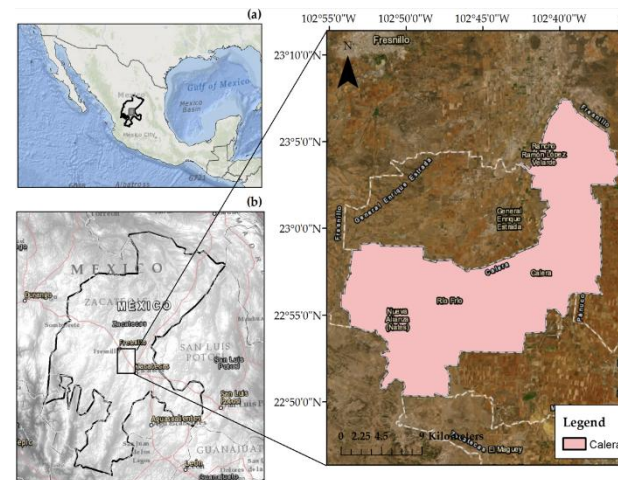
The state of Zacatecas is located between  $21^{\circ} 01'$  and  $25^{\circ} 07'$  north latitude and between  $100^{\circ} 43'$  and  $104^{\circ} 22'$  west longitude. It is made up of 58 municipalities [Figure 1]. It has an area of 75,275 km<sup>2</sup>, representing 3.8% of the Mexican Republic [eighth place in territorial extension]. It has a population of 1,622,138 inhabitants, representing 1.26% of the country's population [INEGI, 2020].

The municipality of Calera de Víctor Rosales has a population of 45,759 inhabitants, representing 2.80% of the state's population [INEGI, 2020]. Most of the municipality's territory belongs to the Fresnillo-Yescas Hydrological Basin of Hydrological Region No. 37 El Salado, is located in the central region of the state of Zacatecas south of the Tropic of Cancer, at  $22^{\circ}57'$  north latitude and  $102^{\circ}47'$  west longitude of the Greenwich meridian.

The average annual temperature of  $16^{\circ}\text{C}$  and an average rainfall of 500 mm, in the center where the municipality of Calera is located, the semi-dry climate and to the south the semi-humid, fits into the characteristics of the temperate semi-dry with a summer of irregular rainfall that can oscillate between 400 and 700 mm and a winter with occasional rains.

The maximum temperatures are recorded in the month of May, in the last three years they have exceeded  $30^{\circ}\text{C}$  and the minimum temperatures in January that can reach  $4^{\circ}\text{C}$  below zero. The prevailing winds flow from southwest to northwest and their action is accentuated from November to April.

### Box 1



**Figure 1**

Study location

[by the authors]

The geological strata of the municipality of Calera are classified within the Quaternary period of the Cenozoic and Mesozoic eras.

Calera is located in the province of the Central Tableland and in the subprovince known as the Llanos and Sierra Potosino-Zacatecana. It is part of the alluvial plain located 2,000 meters above sea level that extends northward from Fresnillo to Cañitas de Felipe Pescador and southeastward to Calera de Víctor Rosales. Its floor is of caliche [petrocalcic horizon], with scattered mountain ranges and elongated strips called “bajíos” [shallows].

These “bajíos” contain deep soils mostly used for agriculture. In some ways, these “bajíos” can be considered water-collecting strips that, during the rainy season, have water reserves far exceeding those corresponding to precipitation. The municipality of Calera generally corresponds to the type of arid and semi-arid regions, and the varieties are gypsisols, which correspond to the ochric horizon, whose main characteristic is their lack of organic matter.

One of the types in the region is the luvic gypsisol, with a lithic bedrock and a thickness of 20 to 45 cm with medium texture. Another type of gypsisol has a bedrock of petrocalcic rock [caliche] with a medium texture and a thickness of 30 to 70 cm [commonly called red earth]. In smaller quantities than gypsisol, there are areas of yermosol, also of the ochric horizon.

Another variety of soil found in Calera is the castañozem, which belongs to the mollic horizon, which is luvic without salinity; its bedrock is petrocalcic rock, has a medium texture, and its thickness ranges from 35 to 80 cm. There are also soils classified as pheozem, belonging to the mollic horizon with moderate productive potential. There are also strips of eutric lithosol with a thickness of approximately 10 cm. They have little productive potential and can only withstand very moderate grazing.

The Calera or Matamoros Stream originates on the border with the Santiago River Hydrological Region. Its main course runs south to northeast, crossing the urban area of Calera through the center. The watershed area is 47.98 km<sup>2</sup>; the stream has an average gradient of 0.011%, with an elevation range between 2428.7 and 2227 m above sea level. Other streams form near this watershed and eventually discharge into the Sedano Lagoon.

Settlements located on the banks or near riverbeds are exposed to a high risk of flooding, depending on their proximity to the riverbed and the characteristics of their topography. Generally, the plains can generate floodplains, the severity of which will depend on the intensity of the rainfall that occurs in the catchment basins and how they can be regulated in the dams that are located upstream of the population. Considering this, the flows will be estimated for different return periods [Tr] and the flood scenario will be simulated for a Tr of 10,000 years.

### Geomorphological and Topographic Characterization

Hydrologically, the basin functions as a large collector that receives precipitation and transforms it into runoff. This action is a function of a large number of parameters that influence the hydrological behavior of the basin. To date, it has been proven that some indices and characteristics influence the hydrological response of the basin [Campos Aranda, 1998].

They are the starting point for hydrological analyses of the basin [Table 1].

## Box 2

Table 1

Hydrological features

Data	Parameter/equation	References
Compactness coefficient	$K_c = \frac{0.28 P}{\sqrt{A}}$	Horton 1940, Viesman 1989, Lisle 1977
Elevation	MDE	Inegi, 2020
Channel length	MDE	Inegi, 2020
Elongation ratio	$R_e = 1.128 \frac{\sqrt{A}}{L}$	Strahler 1957
Stream density	$F = \frac{\sum N_i}{A}$	Strahler 1957
Area [A]	A = Basin area [km <sup>2</sup> ]	Strahler 1957
Perimeter [P]	P = Basin perimeter [km]	Smith, K.G, 1957
Main channel length [Lc]	Lc = Length of main channel [km]	Horton 1940, Strahler 1957, Smith, K.G, 1957
Stream order [u]	u = Stream order [dimensionless]	Horton 1940, Strahler 1957, Smith, K.G, 1957
Total number of flow channels [Nu]	Nu = Number of flow channels	Horton 1940, Strahler 1957, Smith, K.G, 1957
Total channel length [Lu]	Lu = Length of all flow channels in the basin [km]	Horton 1940, Strahler 1957, Smith, K.G, 1957
Drainage density	$D_d = \frac{\sum l}{A}$	Horton 1940, Strahler 1957, Smith, K.G, 1957

It is called a topographic survey when the extension is topographic [less than 30 km] or geodetic [more than 30 km], they can be cadastral, they are carried out in urban areas, cities and municipalities to obtain the inventory of real estate, basis of property taxes and regulatory plans in this research a hydrographic survey was carried out, which allows to obtain the description and study of the different bodies of water such as oceans, lakes and rivers obtaining the configuration of the underwater terrain.

In this research the latter is used to generate cross sections of the stream bed equidistant every twenty meters [20] meters based on a UTM coordinate system, georeferenced, the longitudinal profiles along the axis of the stream must record the bottom of the channel, as well as both margins, detailed topographic plans must be obtained at a horizontal scale of 1:1000 and a vertical scale of 1:100, with contour lines equidistant every 0.50 m, covering an area of approximately half a hectare, or that area that allows the discharges to be delimited.

### Temporal rainfall series

The monitoring and recording of maximum rainfall over 24 hours is controlled by three climatological stations, with geographic coordinates [Table 2], which are managed by CONAGUA. These provide information on precipitation, temperature, relative humidity, evaporation and winds.

#### Box 3

**Table 2**

Climatologic stations of the Arroyo Matamoros's basin

#	Station	Municipality	Latitude	Longitud de	m.a.s.l . [m]
32003	Calera	Calera	22°54'30.96"	102°39'34.9"	2,097
32002	Boca del Tesorero	Jerez	22°49'25"	102°57'6"	2045
32173	El Peñasco	Gral Enrique Estrada	22°59'34.08"	102°50'13.9"	2,246

The annual historical data for the period [1989-2018], of the maximum 24-hour precipitation of the aforementioned stations are shown in Table 3.

#### Box 4

**Table 3**

Maximum 24-hour precipitation data [mm] for the Arroyo Matamoros watershed.

Year	Boca del Tesorero	Calera	El Peñasco
1989	39.5	39	-
1990	31.8	70.3	-
1991	48	57.5	-
1992	40	28.5	-
1993	49.4	30.4	-
1994	64	42	-
1995	51	31	-
1996	53.5	34.5	-
1997	25.6	30.8	-
1998	44.5	45.9	-
1999	34	33.7	-
2000	45.6	47	-
2001	32.9	37.5	-
2002	60	72	-
2003	60	36.8	36.3
2004	43.2	33.6	43.0
2005	29	27	30.7
2006	75.1	38.6	78.6
2007	40	39.2	30.3
2008	46.5	32	49.8
2009	43	56.2	35.0
2010	26.7	66.5	56.7
2011	31	52.2	25.0
2012	31.2	30.7	31.0
2013	55	45.4	55.0
2014	50.6	38.8	64.6
2015	55.7	46	69.0
2016	30.8	43	44.0
2017	32.4	29.4	45.5
2018	39.6	70.2	46.5

### Design Expenditure

The conversion of precipitation to runoff will be carried out using the United States Soil Conservation Service [USDA] method, using the N curve number. This is a robust, acceptable, and simple method for determining excess rainfall after the infiltration process. It produces runoff in ungauged basins, both urban and non-urban.

This method determines the runoff coefficient using [Equation 1].

$$C = \frac{[P_{mc} - 508(\frac{1}{N} - \frac{1}{1000})]^2}{P_{mc}[P_{mc} + 2032(\frac{1}{N} - \frac{1}{100})]} 100. \quad [1]$$

where  $P_{mc}$  is the average annual precipitation in centimeters and N is the runoff number or curve number.

To determine the N value, a specific combination of soils, vegetation cover and land use, hydrologic group, and antecedent moisture conditions [previous rainfall] will be identified. Hydrologic soil groups and N values will be determined using a combination of soil texture and vegetation cover [USDA, 2005]. A design precipitation and flow rate will be projected for a return period of 10,000 years. However, design precipitation will also be calculated using different hydrologic methods, and the one that best fits the watershed under study will be considered.

### Flood Simulation

To simulate flooding due to peak rainfall, open-source software was used. HEC-RAS 5.0 is designed to perform one-dimensional hydraulic calculations for a complete network of natural and constructed channels. It is open-source software

[<https://www.hec.usace.army.mil/software/hecras/>].

HEC-RAS 5.0 contains four one-dimensional analysis components for: [1] steady-flow water surface profile calculations; [2] unsteady-flow simulation; [3] moving-boundary sediment transport calculations; and [4] water quality analysis. A key element is that all four components use a common geometric data representation and common geometric and hydraulic calculation routines.

In addition to the four river analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are calculated.

Steady-flow water surface profiles are modeled for gradually varied flow. The system can handle an entire channel network, a dendritic system, or a single river reach. The steady-flow component is capable of modeling subcritical, supercritical, and mixed water surface flow regimes.

The basic calculation procedure is based on the solution of the one-dimensional energy equation [Table 4]. Energy losses are evaluated by friction [Manning's equation] and contraction-expansion [coefficient multiplied by the change in velocity head]. The momentum equation can be used in situations where the water surface profile is rapidly varied [Dávila, 2023].

#### Box 5

Table 4

2D Shallow Water Equations.

#	Equation
1	$\frac{\partial H}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = r$
2	$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left( \frac{p^2}{h} \right) + \frac{\partial}{\partial y} \left( \frac{pq}{h} \right) = - \frac{n^2 p g \sqrt{p^2 + q^2}}{h^2} - g h \frac{\partial H}{\partial x} + p f + \frac{\partial}{\rho \partial x} (h \tau_{xx}) + \frac{\partial}{\rho \partial y} (h \tau_{xy})$
3	$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{pq}{h} \right) + \frac{\partial}{\partial y} \left( \frac{q^2}{h} \right) = - \frac{n^2 q g \sqrt{p^2 + q^2}}{h^2} - g h \frac{\partial H}{\partial y} + q f + \frac{\partial}{\rho \partial x} (h \tau_{xx}) + \frac{\partial}{\rho \partial y} (h \tau_{yy})$

where:  $H[x,y,t] = z[x,y] + h[x,y,t]$  is the surface elevation [m];  $z$  is the cell elevation in Cartesian coordinates  $[x,y]$ ;  $h$  is the water depth [m];  $p=hu$  and  $q=hv$  are the specific flux in the  $x$  and  $y$  directions [ $m^2/s$ ];  $u$  and  $v$  are the velocities in  $x$  and  $y$ , respectively;  $r$  is the net rainfall [m];  $g$  is the acceleration of gravity [ $m/s^2$ ];  $n$  is the Manning roughness coefficient [ $s/m^{1/3}$ ];  $\rho$  is the water density [ $kg/m^3$ ];  $\tau_{xx}$ ,  $\tau_{yy}$  and  $\tau_{xy}$  are the components of the stress tensor; and  $f$  is the Coriolis parameter [ $1/s$ ]. The above equations are solved with an implicit finite volume scheme.

## Results

### Geomorphological Characterization

The Matamoros Creek flows through the town of Víctor Rosales, Zacatecas, Mexico. Its source is located at 2,227 meters above sea level, with geographic coordinates of  $102^\circ 46' 04.64''$  West,  $22^\circ 54' 59.15''$  North. It is located between the Mesa del Centro and the Sierra Madre Occidental, with a drainage area of  $47.98 \text{ km}^2$ . Its elevation varies from 2,227 to 2,428.7 meters above sea level, and its main channel is 18.34 km long [Figure 2]. According to the Chow 1982 classification, it is considered a small basin.

#### Box 6

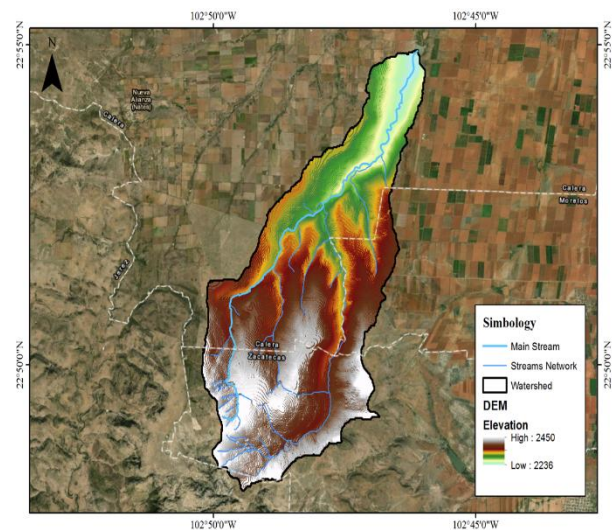


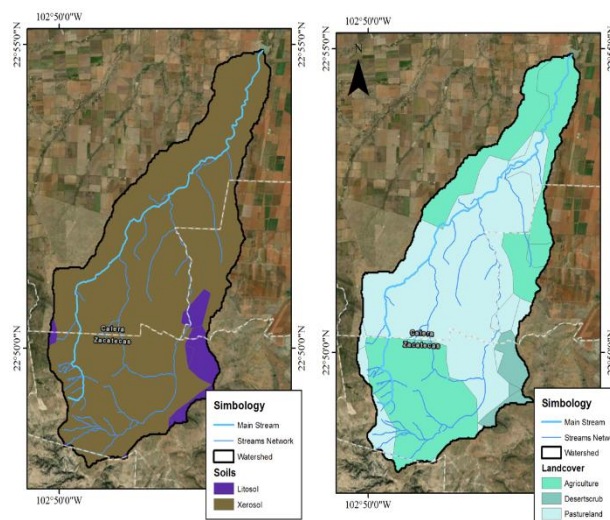
Figure 2

Arroyo Matamoros's basin

The compactness coefficient was 1.41, indicating an elongated basin with high relief. The elongation coefficient of 0.41, with a slope of 0.011 to 0.019 m/m, is a mature basin, considering the hypsometric curve, indicating that the channels through which water flows are well-defined.

The predominant vegetation is agricultural-livestock-forestry with an area of  $20.66 \text{ km}^2$ ; natural grassland  $25.44 \text{ km}^2$ ; and Crassula scrub  $1.88 \text{ km}^2$ . This factor influences the rainfall-runoff relationship, as does the predominant soil type [lithosol and xerosol] [Figure 3]. Generally, this type of vegetation generates runoff rates ranging from 45 to 60.

## Box 7



**Figure 3**  
Vegetation and soil type

## Determining the 24-Hour Maximum Rainfall

The maximum daily rainfall data were fitted to various probability distributions, considering the smallest standard error [Table 5]. The best distribution was the simple Gumbel, which was used to estimate the design rainfall for different return periods.

## Box 8

## Table 5

Probability distributions in Arroyo Matamoro's basin

Boca del Tesorero	del Calera	El Peñasco	Average
$\mu =$	42.919	$\mu =$ 40.5	$\mu =$ 44.3
$\sigma =$	11.567	$\sigma =$ 11.8	$\sigma =$ 16.2
$\gamma =$	0.698	$\gamma =$ 0.80	$\gamma =$ 0.80
$\kappa =$	3.456	$\kappa =$ 3.65	$\kappa =$ 3.59
10000	105	100	100
	00	69	00
		00	76
			00
			44

For the intensity-duration-return period [I-D-Tr] curves, the Bell method [1969] was used. The I-D-Tr curves were generated based on the maximum rainfall data fitted with Gumbel [Table 6].

## Box 9

## Table 6

Intensity–Duration–Return Period of the weighted average of the basin stations.

Tr	Intensidad (mm/hr) - Duración (hr) - Período de Retorno															
	0.083	0.167	0.333	0.667	1	1.667	2	2.5	3	3.45	3.5	4	5	6	24	
	Duración (min)															
	5	10	20	40	60	100	120	150	180	207	210	240	300	360	1440	
5	137.9	103.2	71.98	48.1	37.48	27.08	24.06	20.78	18.41	16.77	16.61	15.19	13.06	11.54	4.402	
10	163.2	122.1	85.18	56.92	44.36	32.05	28.47	24.59	21.79	19.85	19.66	17.97	15.46	13.65	5.209	
20	188.5	141.1	98.37	65.74	51.23	37.01	32.88	28.4	25.16	22.92	22.7	20.76	17.85	15.77	6.016	
50	221.9	166.1	115.8	77.4	60.31	43.57	38.71	33.43	29.63	26.99	26.73	24.44	21.02	18.56	7.082	
100	247.2	185	129	86.22	67.18	48.54	43.12	37.24	33	30.06	29.77	27.22	23.41	20.68	7.889	
200	272.5	203.9	142.2	95.04	74.05	53.5	47.53	41.05	36.38	33.14	32.82	30.01	25.81	22.79	8.696	
500	305.9	228.9	159.7	106.7	83.14	60.07	53.36	46.08	40.84	37.2	36.85	33.69	28.97	25.59	9.763	
1000	331.2	247.9	172.8	115.5	90.01	65.03	57.77	49.89	44.21	40.28	39.89	36.47	31.37	27.71	10.57	
2000	356.4	266.8	186	124.3	96.88	70	62.18	53.7	47.59	43.35	42.94	39.25	33.76	29.82	11.38	
5000	389.9	291.8	203.5	136	106	76.56	68.01	58.74	52.05	47.42	46.96	42.94	36.93	32.62	12.44	
10000	415.2	310.7	216.7	144.8	112.8	81.52	72.42	62.55	55.43	50.49	50.01	45.72	39.32	34.73	13.25	

## Methods for Estimating Peak Flow

The rational method is probably the oldest model for the rainfall-runoff relationship, dating back to 1851 or 1889. Due to its simplicity, it is one of the most widely used. It assumes that the area studied receives uniform rainfall over a certain period of time, such that runoff in the basin is established and a constant discharge rate is achieved.

This method allows the determination of the maximum discharge caused by a storm, assuming that this is achieved when rainfall intensity is approximately constant for a certain duration, which is considered to be equal to the basin's time of concentration. The peak or maximum discharge is defined by [Equation 2].

Applying the rational method, the following design discharges are obtained [Table 7].

$$Q_p = 0.278CIA[2]$$

where  $Q_p$ = Maximum or peak discharge, in  $m^3/s$ ,  $C$ = Dimensionless runoff coefficient,  $I$ =Average rainfall intensity for a duration equal to the basin's time of concentration, in  $mm/h$ ,  $A$ =Basin area, in  $km^2$ .

## Box 10

## Table 7

Peak flow designs applying the rational method [ $m^3/s$ ].

Tr [years]	Chen	Kuishling	Bell
50	75.15	11.76	120.85
100	90.86	15.84	149.14
200	107.41	20.25	178.83
500	130.40	26.42	219.86
10,000	212.52	44.42	364.18

Mockus developed a synthetic triangular unit hydrograph. The peak discharge is obtained from its geometry or behavior using Equation 3:

$$q_p = \frac{0.556AP_e}{nT_p} \quad [3]$$

where  $q_p$  = Peak discharge of the unit hydrograph, in  $m^3/s$ -mm,  $A$  = Basin area in  $km^2$ ,  $P_e$  = Effective precipitation [mm],  $n$  = Peak reduction factor, which is calculated using the following Equation 4:

$$n = 2 + \frac{A - 250}{1583.33} \quad [4]$$

For basins with an area greater than 250  $km^2$ , and  $n = 2$  for basins smaller than 250  $km^2$ .  $T_p$  = Peak time, equal to the time between the start and maximum of direct runoff in hours, calculated using Equation 5.

$$T_p = 0.5 D + Tr \quad [5]$$

where  $Tr$  is the return period and  $D$  = Duration of effective precipitation, considering  $D = tc$ .

The return time is estimated using the time of concentration  $tc$ , considering that  $Tr = 0.6tc$ . Therefore, the time to peak is calculated according to Equation 6:

$$T_p = 0.5D + 0.6 \quad [6]$$

A discharge for a return period of 10,000 years is obtained using Chen's excess rainfall method: 193.20  $m^3/s$ . When compared with the estimate using the rational method, there is a difference of 19.32  $m^3/s$ . Some authors [Joko et al., 2022; Zeda et al., 2024] have found similar values; that is, the rational method reports higher values, which is why it has been recommended for small watersheds where urban use predominates.

### Simulation models

The simulation was performed using the HEC-RAS 5.0 model. The model's geometry input data were obtained from topography processing in HEC-GeoRAS, and the flow data were obtained from the described models. The water surface profile is calculated by the simulator, which considers one section to the next by solving the Energy Equation [Equation 7] using an iterative procedure called the Standard Step Method

[<https://www.hec.usace.army.mil/software/hec-ras/features.aspx>].

$$Z_2 + Y_2 + \frac{a_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{a_1 V_1^2}{2g} + h_c \quad [7]$$

The HEC-RAS 5.0 model can hydraulically simulate the design flow rate considering a subcritical, supercritical, or mixed flow regime. The specific force equation is used in the model to determine which flow regime is the majority or controlling flow regime, as well as the location of any hydraulic jumps.

The equation for the specific force is derived from the momentum equation. For a very short channel reach, the external friction force and the force due to the weight of the water are very small and can be ignored [HEC-RAS 5.0 Reference Manual, 2015].

The momentum equation reduces to the following Equation 8:

$$\frac{Q_1^2 \beta_1}{g A_1} + A_1 \bar{Y}_1 = \frac{Q_2^2 \beta_2}{g A_2} + A_2 \bar{Y}_2 \quad [8]$$

where:  $Q$  = flow rate at each section,  $\beta$  = momentum coefficient [similar to alpha],  $A$  = total flow area,  $Y$  = depth from the water surface to the centroid of the area,  $g$  = gravitational acceleration.

When the specific force is applied to natural channels, the equation reduces to Equation 9:

$$SF = \frac{Q^2 \beta}{g A_m} + A_T \bar{Y} \quad [9]$$

where  $A_m$  = Area of the flow in which there is movement.  $A_T$  = Total area of the flow, including ineffective flow areas.

The equation consists of two terms: the first term is the momentum of the flow passing through the channel cross section per unit time.

This part of the equation is considered the dynamic component. The second term represents the momentum of the static component, which is the force exerted by the hydrostatic pressure of the water.

The sum of the two terms is called the specific force [Chow, 1959]. Mixed-regime calculations for steady-state flow analysis use the water surface in a subcritical regime based on known downstream boundary conditions.

During subcritical regime calculations, all locations where the model defaults to critical depth are flagged for further analysis.

The results generated through HEC-RAS 5.0, considering the calculated design flow rates and satellite remote sensing images, as well as field topography refinement, are presented below.

During the physical surveys, the physical characteristics of the channel material were observed, both at the bottom and on the banks and floodplains [Figure 3], in order to have elements to propose Manning coefficient values.

**Box 11**



**Figure 3**  
Arroyo Matamoros's basin

Hummel, Duan and Zhang [2012] in ephemeral channels in the state of Arizona in the United States of America compares the models for unsteady and semi-unsteady flow in the simulation with sediment transport and describes the way in which these models work with hydraulic simulation, recommends that the coefficients used for Semi-desert Zones be those referenced in Table 8 and Figure 4.

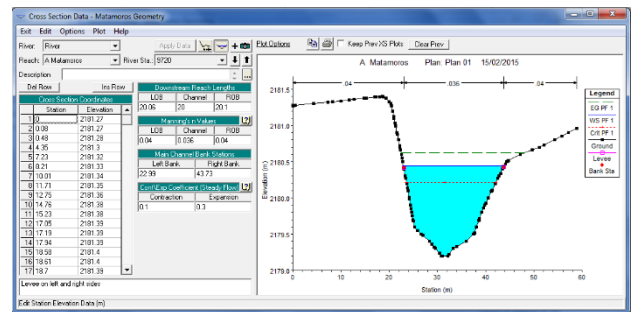
**Box 12**

**Table 8**

Simulation coefficients.

<i>Manning coefficient</i>		
Left	River	Right
0.04	0.036	0.04
<i>Coefficients</i>		
Expansion	0.3	
Contraction	0.1	

**Box 13**

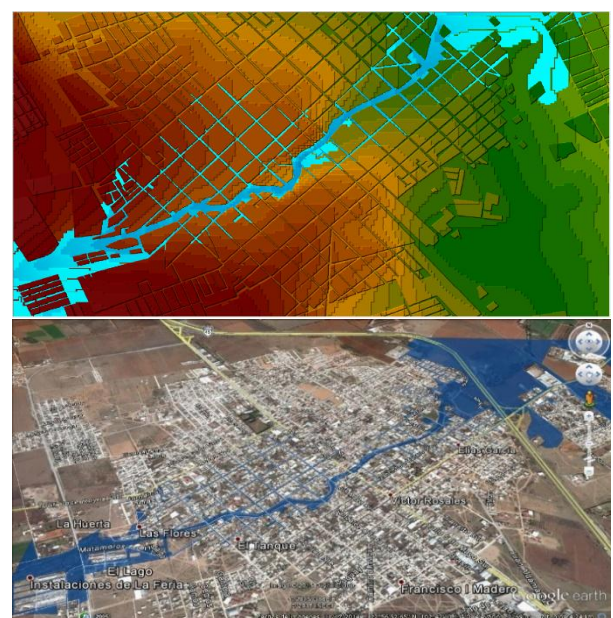


**Figure 4**

Coefficients used in Arroyo Matamoros's simulation

With the modeling of the danger zones, it was obtained that for a controlled discharge with a return period of 10,000 years the affected urban area would be 143 hectares, which could affect 5,940 inhabitants of the municipality of Calera de Víctor Rosales, Zacatecas, Mexico [Figure 5].

**Box 14**



**Figure 5**

Determination of flood-prone areas in Calera de Víctor Rosales [View on Hec-Ras] and [View on Google Earth]

## Conclusions

The extraordinary flooding in the reservoir, with a Tr of 10,000 years, resulted in an elevation of 15 cm [2233.75 m above sea level] above the crest [2233.6 m above sea level].

Therefore, under this scenario, the reservoir is considered a hydrological risk. Hazard zone modeling showed that, for a controlled discharge with a 10,000-year return period, the affected urban area would be 143 hectares, potentially affecting 5,940 residents of the municipality of Víctor Rosales.

Proposed risk mitigation actions:

By raising the dam by 1.00 m, the water level in the reservoir will be 0.85 m below the crest for a 10,000-year return period. This will prevent overflows that could cause failure of the graded material dam. The information obtained is used to plan the growth of urban areas, avoiding construction in floodplains.

Likewise, hydraulic conduction works, control structures, and communication structures must be designed to allow the residents of the municipal seat of Calera, Zacatecas, to live and move around safely in the face of adverse weather events.

Furthermore, the areas susceptible to flooding were identified, as well as the areas where greater care must be taken to expand their hydraulic section, in order to safeguard the physical integrity of the people living along the banks of the riverbed. Likewise, the data contained in this work allows for the evaluation of the hydraulic structures currently available in order to analyze their viability and plan any necessary works, such as the demolition and expansion of the area of street crossings, which would give better hydraulic performance to the channel that crosses the municipal head of Calera de Víctor Rosales, and also to line the entire stream with concrete at its crossing with the head, since with an area of 30 m<sup>2</sup>, the flow that could pass through the crossings would be 120 m<sup>3</sup>/s, whose flow corresponds to a return period of 500 years.

## Declarations

## Conflict of interest

The authors declare no interest conflict.

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## Author contribution

All authors contributed to the project idea, research method and technique.

## Availability of data and materials

Further information could be requested to the main author.

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