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Preliminary assessment of the risk of river overflow in the presence of a bridge using HEC-RAS and LiDAR topography

Evaluación preliminar del riesgo de desbordamiento de ríos en presencia de un puente mediante HEC-RAS y topografía LiDAR

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Abstract

The objective of this study is to evaluate the risk of flooding due to the overflowing of the Laja River around the bridge located on the Santa Catarina de Peña-Perico de Cornejo Road section in the municipality of Salamanca, Guanajuato, Mexico. The evaluation is carried out through modeling and computational simulation under normal and extreme flow conditions. The software used is HEC-RAS under steady flow and establishing uniform flow as the boundary condition for the inflow and outflow in the domain. The modeling is performed entirely with open-access information available in databases of governmental agencies on the Internet. The methodology used is proposed as an important support in the monitoring and/or forecasting of river hydrodynamics in areas of interest such as the location of bridges, allowing the identification of risk areas and scenarios quickly and economically, so that efforts and resources can be focused on these critical scenarios with more extensive studies, including sediment transport, updated and more accurate topographic data, as well as extending the projection of hydrological variables. In the case study presented, the flooding problem was identified, and it is recommended to gather information in the field to complement the study and establish adequate solutions.

Flood, Hydrodynamics, Computational simulation

Resumen

El objetivo del presente estudio es evaluar el riesgo de inundación por desbordamiento del Río Laja en la zona del puente ubicado sobre el tramo carretero Santa Catarina de Peña-Perico de Cornejo en el municipio de Salamanca, Guanajuato, México. La evaluación se realiza a través de modelado y simulación computacional bajo condiciones normales y extremas del caudal. El programa utilizado es HEC-RAS bajo condiciones de flujo permanente y estableciendo flujo uniforme como condición de frontera de entrada y salida del flujo en el dominio. El modelado se realiza totalmente con información de acceso libre disponible en bases de datos de dependencias gubernamentales en Internet. La metodología empleada se propone como un apoyo importante en el monitoreo y/o pronóstico de la hidrodinámica de ríos en zonas de interés como lo pueden ser la ubicación de puentes, permitiendo identificar zonas y escenarios de riesgo de forma rápida y económica, de esta forma tanto los esfuerzos como los recursos se pueden centrar en estos escenarios críticos mediante estudios más extensos, en los que se incluyan transporte de sedimento, datos topográficos actualizados y de mayor precisión, así como, ampliar la proyección de variables hidrológicas. En el caso del estudio presentado se identificó la problemática de inundación, donde se recomienda recabar información en campo para complementar el estudio y establecer soluciones adecuadas.

Inundación, Hidrodinámica, Simulación Computacional

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Introduction

This article addresses two fundamental aspects in urban development planning, floods and bridges. According to Hernández-Uribe *et al.* (2016) UNESCO (United Nations Educational, Scientific and Cultural Organization) points out that floods account for 50% of water-related disasters worldwide, even above famines, droughts and epidemics. In economic terms, it is estimated that floods are responsible for 20% of total losses in Asia in the last 30 years (Dutta, 2003).

Douben (2006) notes that, on a global scale, the frequency of floods is increasing, although the reliability of flood data tends to overestimate this trend. This global increase is mainly due to relatively large floods with a recurrence interval of between 10 and 20 years.

Thus, floods are a sensitive issue that requires global efforts to estimate the areas at risk and to assess both hazard and vulnerability to flooding. Recent studies show that Latin America is no exception (Segura-Gutiérrez and Vargas-García, 2022; Curay-Casaverde, 2022; Calvo-Siles, 2022; Pinto-Argel, 2022; Cieza-Guerrero, 2022; Hernández-Uribe *et al.*, 2016).

In the state of Guanajuato, the issue of floods has also been closely followed, from the social and hydrological perspective (Woitrin-Bibot *et al.*, 2015) and punctual analyses of extreme events (Matías-Ramírez *et al.*, 2007).

On the other hand, bridges with crucial elements in the land communication network that catalyze urban development. However, a negative point is pointed out by Pregnolato *et a*l. (2022): Bridges act as bottlenecks for surrounding roads and, therefore, any service disruptions can disrupt community access and connections, impair emergency planning and evacuation routes, and impact economies and businesses.

Because of the importance of bridges and the impact they suffer from flooding, many efforts are focused on estimating flood risk analysis.

The present work aims to implement a methodology based on the use of freely available information in databases on the Internet to perform preliminary assessments of the probability of flooding in the vicinity of bridges quickly and inexpensively. The results of the assessments will allow efficient use of available resources, prioritizing high-risk regions.

The research is presented under the following scheme. The Study Area section describes the location, selection criteria and characteristics of the chosen region. The software used, the calculation methods, the boundary conditions and the selection of model tuning parameters are presented in the Modeling section. The flow rates that define the simulated scenarios are presented in the Simulations section, while the resulting water level and its corresponding analysis are included in the Results and Analysis section. Finally, in Conclusions, the most relevant results are summarized and opportunities for improvement are defined.

Study area

The study area corresponds to a stretch of the Laja River where the bridge that connects the communities of Santa Catarina de Peña and Perico de Cornejo is located (14 Q, 282162.00 m E, 2270615.00 m N), see Figure 1. The area is located in the municipality of Salamanca, Guanajuato, Mexico; the bridge provides a quick connection between a region dedicated mainly to agriculture and the Querétaro-Irapuato highway, which integrates the industrial corridor of Guanajuato, one of the most active trade routes in the central region of the country.

Figure 1 Location of the study area

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The runoff area associated with the selected bridge is 11,945.40 km^2, this area is approximate to that of the R. Laja watershed (key RH12H) of 12,093.83 km^2, the difference is due to the fact that the bridge is located slightly before the outlet of the watershed as shown in Figure 2.

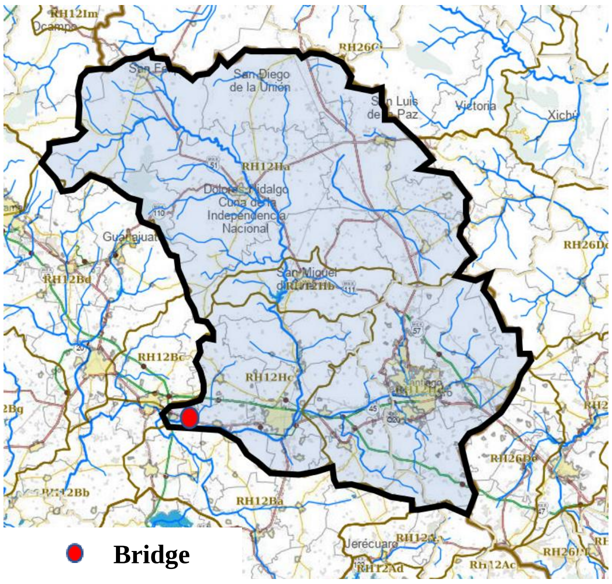

Figure 2 R. Laja watershed and location of the bridge

The climate of the area is semi-warm sub-humid with summer rains of lower humidity. The temperature range is 14 to 20°C and precipitation is 600 to 900 mm. In terms of geology, the area is composed of alluvial soil and in edaphological terms corresponds to a vertisol. Land use is agricultural (INEGI, 2010).

Modeling

HEC - RAS (Hydrologic Engineering Centers River Analysis System) is a hydraulic modeling software that, through the one-dimensional steady flow computation component, determines water surface profiles for steady and gradually varying flow. The system can handle a complete channel network, a dendritic system or a single river reach. The steady flow component is capable of modeling flow surface profiles in subcritical, supercritical and mixed regimes. The basic computational procedure is based on the solution of the one-dimensional energy equation (US Army Corps of Engineers, 2022).

This software also allows simulating flows in natural or artificial channels, as well as determining the water level, so it is also used in flood studies.

The basic requirements for calculating one-dimensional flow within HEC-RAS: flow data and geometry, are described below.

Flow

The type of flow used is permanent, since we worked with constant flows and not with hydrographs.

With the help of the Simulador de Flujos de Agua de Cuencas Hidrográficas (SIATL), the nearest hydrometric station to the study area, station 12238 (see Figure 3), was identified and the record of the maximum annual discharge was extracted from the Banco Nacional de Datos de Aguas Superficiales (BANDAS).

Figure 3 Location of hydrometric station 12238

The record of station 12238 contains the maximum annual discharge from the year 1929 to 2014.

Regarding the boundary condition, since we did not have information on the water level in the study area, we started with the normal discharge, so the section of the channel to be evaluated was extended upstream considering the beginning in a relatively straight section to reduce the initial error and avoid a significant affectation in the area of interest, the bridge area (Figure 5).

Geometry

The geometry data, for the present study, consists of the delimitation and configuration of the channel through its length, cross sections and energy loss coefficients (friction, expansion and contraction).

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The geometry of the model was established with the help of HEC-GEORAS software from the LiDAR data obtained from the F14C63F3 chart provided by INEGI (National Institute of Statistics and Geography), see Figure 4.

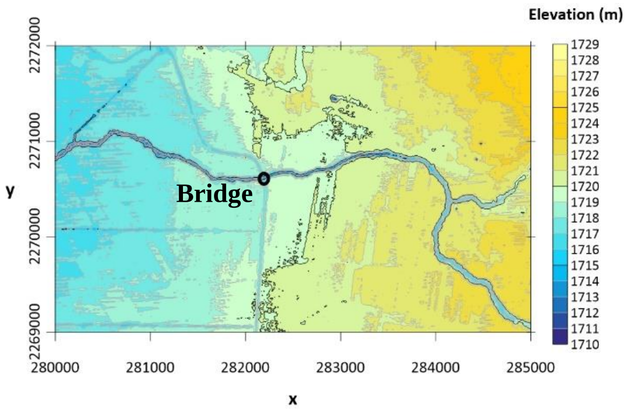

Figure 4 Contour map of terrain elevations, UTM coordinates

The model domain is shown in Figure 5 and was established considering the channel configuration (length) and floodplains in the study area (width). The length of the river was approximately 1600 m, while the width of the domain was approximately 450 m (200 m in both flood plains, right and left, and 50 m from the main channel, approximately).

On the other hand, cross sections were set at every 100 m by defining the Mannng roughness coefficient based on information from the HEC-RAS manual. The main channel was assigned a coefficient of 0.045, since it was considered a clean channel with little vegetation and stones, with some pools and shallows; while the flood plains were assigned a coefficient of 0.040, since they were plains with mature crops in rows.

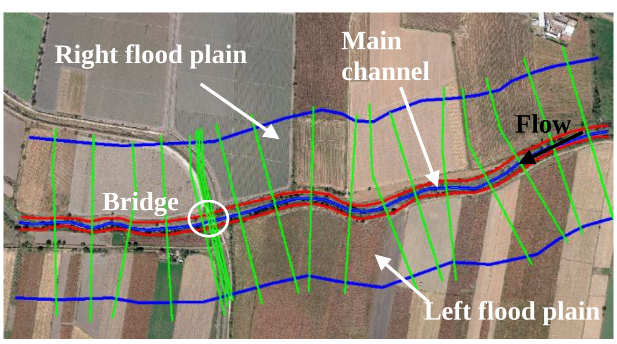

Figure 5 Domain. Main channel, flood plains and cross sections

For the modeling of the bridge, the four mandatory sections were established for the correct hydraulic calculation. The contraction and expansion lengths were estimated at 15 and 30 m, respectively. Since it is a bridge with a span of 22 m, a deck width of 3.5 m, with 3 oval piers separated by 6.5 m and abutments with straight walls, as shown in Figure 6, the moment balance method was chosen for the hydraulic analysis of the bridge. The drag coefficient (Cd) was assigned 0.32 and the pier shape coefficient K was 0.9.

Figure 6 Bridge
Source: (Google Earth) Simulations

The 84 annual peak discharges, corresponding to the 84 years of the record of hydrometric station 12238, were analyzed to obtain the associated return periods using equation 1 according to Aparicio-Mijares (2008). The results are presented in Graph 1.

$$Tr = \frac{n+1}{m} \qquad (1)$$

where:

Tr =Return period

n =Number of data

m =Number of order in a list from largest to smallest

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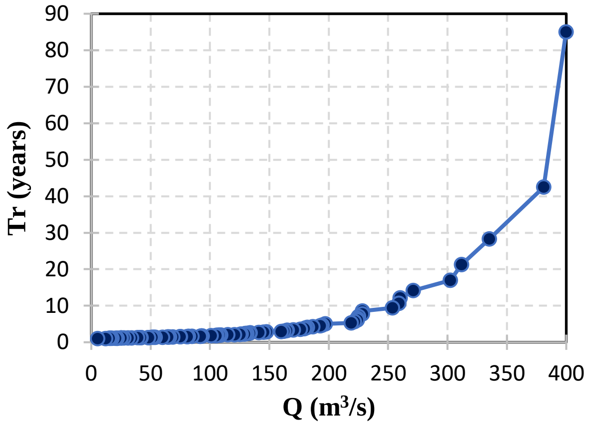

Graphic 1 Return period of the maximum annual expenditure (Q)

The selected simulation scenarios are presented in the following table.

Simulation	Tr (Years)	Q (m^3/s)
1	1	15
2	2	100
3	10	250
4	50	390

Table 1 Simulation scenarios

Results and Analysis

The results presented below correspond to the free water surface elevation (WS), the ground elevation (Ground) is used as a reference and the banks of the main channel (Bank Sta) are indicated.

For each simulation, the calculated water elevation is shown for the bridge cross section and the entire domain with a 3D view to locate flood zones. For the first simulation, corresponding to a 1-year return period and an associated flow of 15 m^3/s, the water level in the bridge section presents an elevation of 1714.8 m, and a discharge of 2.20 m as shown in Figure 7. On the other hand, Figure 8 shows that the flow is contained entirely within the main channel.

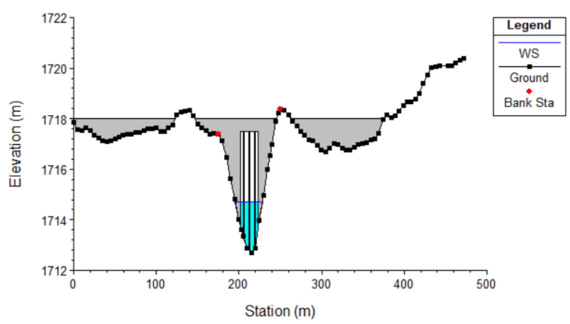

Figure 7 Water elevation in the bridge section. Q=15 m^3/s

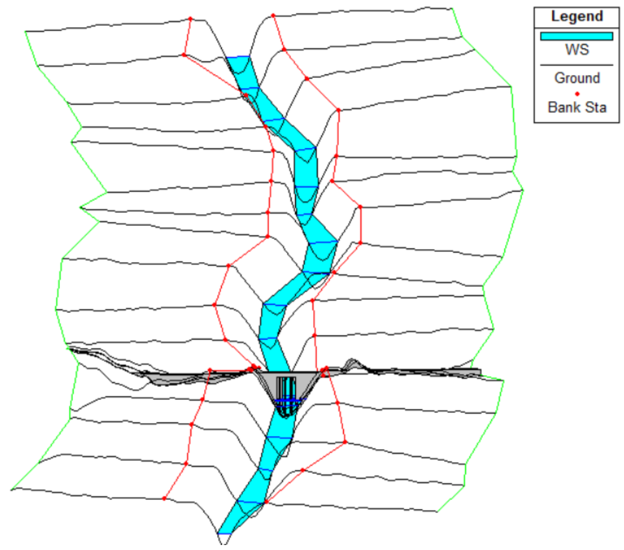

Figure 8 Water elevation in the domain. Q=15 m^3/s

When evaluating the flow of 100 m^3/s corresponding to the return period of 2 years, the increase in the water surface is notorious, registering an elevation of 1716.8 m with an associated 4 m of water flow; however, there is still 0.8 m to reach the bridge deck (see Figure 9).

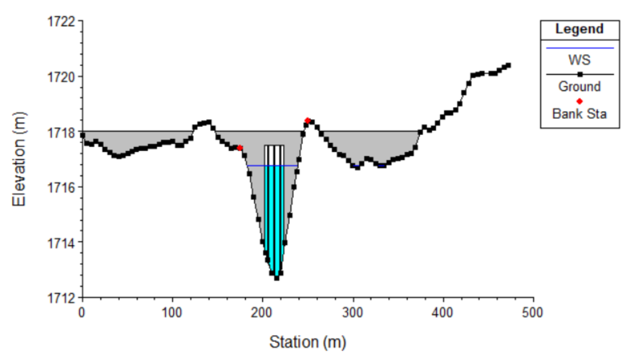

Figure 9 Water elevation in the bridge section. Q=100 m^3/s

The obstacle that the bridge represents to the flow is already noticeable upstream of the bridge with a slight increase in the width of the free surface associated with the backwater caused, but without being very significant as shown in Figure 10. Also, immediately downstream of the bridge there is flooding in a part of the right plain, which is only associated with the increase in the water surface and the low elevation of the land in that area.

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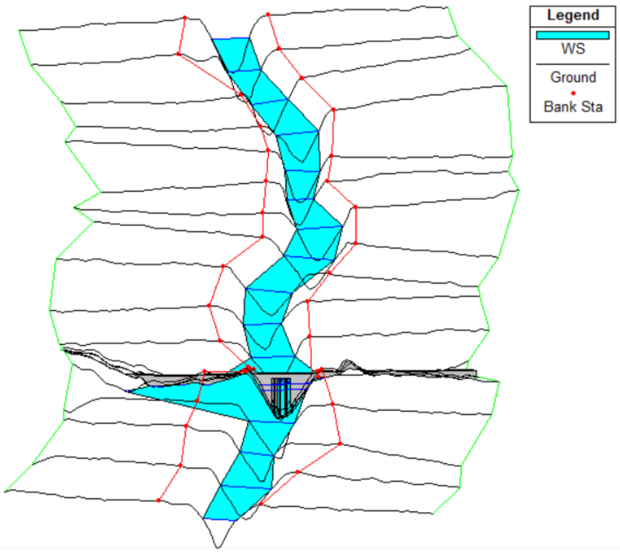

Figure 10 Water elevation in the domain. Q=100 m^3/s

Figure 11 indicates that the bridge deck, 1718 m elevation, is exceeded by the water surface which reached 1718.6 m in the third simulation (T =10 years and Q = 250 m^3/s).

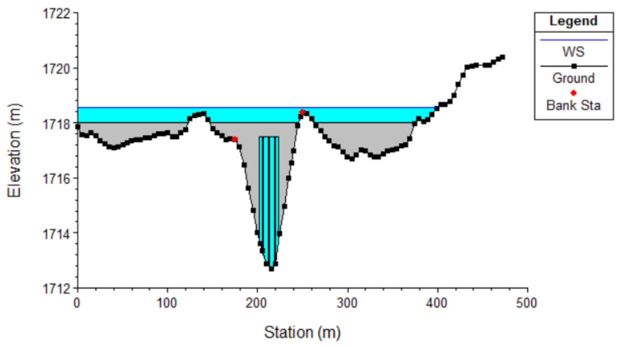

Figure 11 Water elevation in the bridge section. Q=250 m^3/s

The substantial increase in flow and the effect of the bridge on the flow are reflected in increased flooding of the plains mainly in the vicinity of the bridge (see Figure 12).

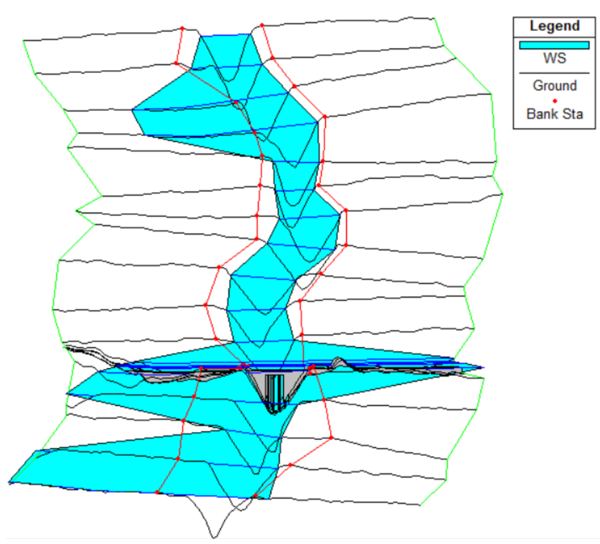

Figure 12 Water elevation in the domain. Q=250 m^3/s

Finally, for simulation 4 (Tr =50 years and Q = 390 m^3/s), the bridge deck is 1.2 m submerged as clearly shown in Figure 13. The main channel is completely overtopped, the right plain is completely flooded, while the left plain has little dry area (see Figure 14).

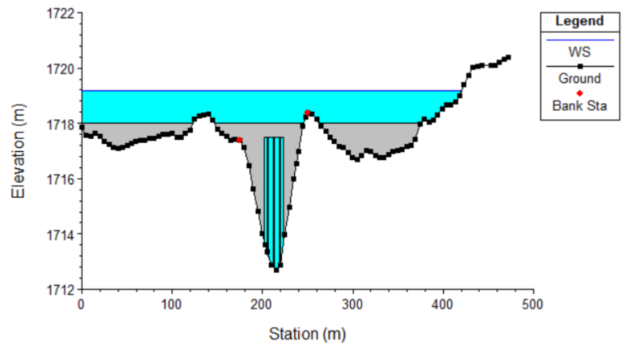

Figure 13 Water elevation in the bridge section. Q=390 m^3/s

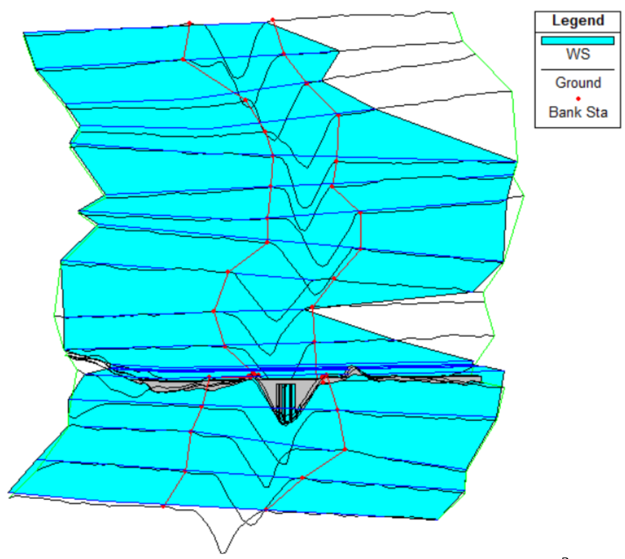

Figure 14 Water elevation in the domain. Q=390 m^3/s.

Conclusions

According to the results and the curve of return periods and maximum annual expenditures, the bridge is subject to flooding conditions with a frequency close to 10 years.

The frequency of flooding is short, but it should be considered that the bridge is small and its affectation does not represent significant losses.

For the case study, the established flood plains were insufficient to map the flooding. However, the objective of the work was achieved by demonstrating the practicality of the assessment methodology.

The usefulness of the proposed methodology to perform a preliminary assessment of the probability of flooding in bridges, based on information available in databases, is demonstrated by monitoring the variation of the free surface with different flows in the vicinity of the bridge.

This methodology can be improved by calibrating the model by region by performing a characterization of the roughness coefficients and of the bridges (sizing).

After identifying the risk scenarios and prioritizing them, the exercise of the economic resource can be carried out efficiently.

The usefulness of the information available in databases is also evident and it is recommended to continue investing in the acquisition of terrain elevations through LiDAR technology.

Acknowledgements

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