Digital methodology to detect vulnerable areas to flooding in urban zones located in the mountains

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Received: September 22, 2022 Accepted: October 25, 2022 Published: November 11, 2022
DOI: https://doi.org/10.56845/rebs.v4i2.73

Abstract: The risk of flooding in cities near riverbeds is a latent concern, especially during the rainy season. A specific case is that of Misantla, located in the State of Veracruz-Mexico, where floods have already caused social and economic damages. For flood prevention, this study proposes a digital methodology based on specialized ArcGIS, HEC-RAS and HEC-GeoRAS software, taking as a case study the urban areas located in mountainous zones of Misantla, Veracruz; likewise, hydrodynamic models supported by field studies and the use of geographic information systems (GIS) were used to know the vulnerable areas. The simulation shows the probable flood zones and the maximum depth levels that flows can reach in extraordinary rainfall events, which is an important element for risk assessment. By forecasting flooding areas, the spatial resolutions used also have a direct impact on mitigating damages caused by flooding. The study results in a risk map showing the sectors of the population most vulnerable to the problem of flooding and information for the design of protection works. In the city of Misantla, the case of this study, the simulated risk map shows that 57.3% of the surface area of the city, particularly the downtown area, is at risk of flooding.

Keywords: digital terrain model; flood map; flood plain; geographic information system; river.

Introduction

One of the negative effects of constant rainfall is floods, which are natural disasters of great magnitude (García *et al.,* 2015) with an immeasurable impact, affecting 170 million people worldwide annually (Patrikaki *et al.,* 2018). Particularly, urban floods have generated highly affecting economic and social consequences (Rufat *et al.,* 2015; Xu *et al.*, 2019; Mark *et al.,* 2018), which, combined with land use change (land use are modifications and interventions that people carry out on a surface to produce), has led to extreme climatic and hydrological conditions, to originate atypical rainfall-runoff events with negative or positive effects for the population (Fitton *et al.,* 2016; Güçlü *et al.,* 2018; *Kundzewicz et al., 2018*; Luo *et al.*, 2018).

Atypical fluvial precipitation on rivers, have the characteristic of causing a rapid response of water volume, exceeding the capacity of its channel and causing overflow in the general trajectory of the river, and subsequently, returning to it when the water begins to descend (Archer & Fowler, 2018). Damage to population centers, crops and infrastructure are usually considerable and, in some cases, with loss of life (Sandink, 2016). In such a case, it can be thought that strategies against the impact of floods, requires studies that identify areas exposed to this phenomenon (Tehrany, 2013), with the purpose of building the corresponding risk maps. In Mexico there is little observational research at a spatial scale necessary to identify potential areas at risk and the prediction of adverse economic impacts (Brody *et al.,* 2018; Khan *et al.,* 2018). Knowledge about such risk areas, is more due to experiences from past phenomena. Such studies can inform adequate flood zone delineation, proper economic management and ensure the safety of the population (Romanescu, 2018). However, the changes in the climatological parameters of the last ten years, do not correspond to what has been learned from the presence of such phenomena.

There are several mapping products available that depict areas susceptible to groundwater flooding, however, they are not comparable in detail to risk maps developed for tidal and fluvial surface water flooding (Morris, 2018). The reliability of flood prediction is limited by the characterization of floods that have multiple causes and hydrological uncertainties due to variability in climate and river morphology (Shah *et al.*, 2018; Ye *et al.*, 2018).

The last decade has seen the development and general acceptance of the concept of integrated flood risk management. This approach strives to balance the effects of river flooding and combines it with risk management, resulting in a diversification of flood management practices that go beyond traditional measures. These practices include giving more space for rivers, re-naturalization of floodplains, and a set of improved information systems, including improved flood forecasting services, promotion of flood risk awareness and self-help capabilities (Grabs, 2016).

In a traditional approach, simulation in rivers is carried out using hydrodynamic models in one dimension –1D–. In cases where the velocity and location of acting forces on structures must be known, it must be carried out using two-dimensional –2D– or three-dimensional hydrodynamic models (Merwad *et al.,* 2008). The main limitation is the availability of inflow data in terms of quality and quantity. In this regard, (Huang & Hattermann, 2018) couple the CaMa-Flood –macro–scale floodplain model and the regional hydrological model SWIM –integrated soil and water model– as a tool for large-scale flood risk assessments.

Nowadays flood risk management is gaining importance to mitigate and prevent flood disasters, and therefore, the analysis of flood risk components is becoming a key research topic (Dottori *et al.,* 2018). Work on the use of multi-criteria analysis for flood vulnerability estimation was presented (Wang *et al.*, 2011), while in (Kourgialas & Karatzas *et al.*, 2011) flood zones were estimated using overlapping layers of GIS –Geographic Information Systems– displaying spatial information and climate.

The use of GIS involves processes of collecting existing information and further processing of the results (Amir *et al.*, 2018). Experiences in research show that a GIS-based analysis of flooding allows to cover the shortage of information and assistance during the validation of modeled results (García *et al.*, 2015), The application of GIS in these studies requires as input data the geometry of the river channel, edge conditions, information on) tributary streams and roughness characteristics of the channel and its edges. The models built with this tool provide results for each cross section of the river and the possible water level allowing an analysis of flood events (Gou *et al.*, 2021; Knel *et al.*, 2005). The simulation of scenarios with this tool shows the probable flood zones and maximum depth, and these can be used for risk assessment (Lee *et al.*, 2018).

This paper proposes a digital methodology using ArcGIS, HEC-RAS and HEC-GeoRAS based on GIS, to build a map of areas vulnerable to flooding –risk map– considering the environmental variables, to simulate flood scenarios in urban communities located in mountain ranges with shallow rivers of rapid response of water flow. These regions are characterized by the highest rainfall, which generates runoffs towards the plains, originating torrential currents.

Materials and Methods

Supported by the ArcGis and HEC-GeoRAS programs integrated in a geographic information system (GIS) environment, we have defined the methodology described in Figure 1, where the following is proposed: 1. data collection in geographic statistical bases, 2. generation of the digital model of the terrain under study, 3. construction of the river profile related to the study area, 4. construction of the topographic trace of the river under study, 5. simulation of scenarios. Use of ArcGIS and HEC-GeoRAS between step 2 and step 3 will allow the generation of the topographic and profile information of the study area.

To demonstrate the usefulness of the digital methodology presented in this article, the investigation was carried out in the city of Misantla, in Veracruz-Mexico. In this place, extraordinary floods have been recorded causing social problems of isolation and damages that have exceeded 500,000 $USD in a single flood event, with damage to communication routes, total loss in housing, and loss of agricultural crops (Rodríguez-Hernández *et al.,* 2020). Misantla is located at coordinates 19° 55' 51.86" N latitude and 96° 51' 6.09" W longitude, at an altitude of 400 meters above sea level, located in the north-central mountainous zone of the state of Veracruz, Mexico (19 ° 56 ′ N and 96 ° 51 ′ W). The climate in the area is classified as hot and humid tropical, with rainfall throughout the year, higher temperatures during the month of June and lower in the month of January, with an average annual temperature between 20 and 26 ° C. The altitude of the area is between 309 and 400 meters above sea level, the average annual precipitation recorded is between 1,900-2,100 mm (Sandoval-Herazo *et al.*, 2018). Misantla belongs to the Tuxpan-Nautla hydraulic basin; the Misantla River is within the perennial river classification and rises in the Sierra Magdalena, Southeastern Mexico, with flow trajectory in a southwest - northeast direction until it flows into the Gulf of Mexico in Las Palmas Bay, after about 65 km of trajectory (Figure 2).

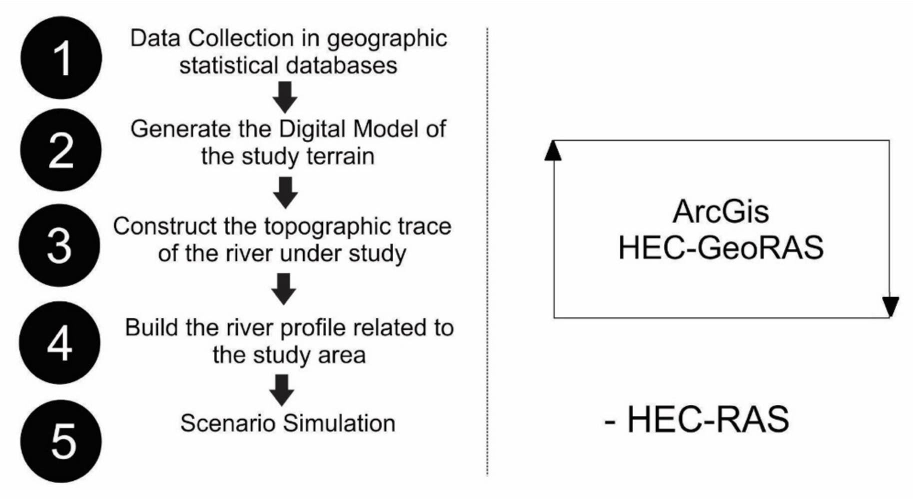

Figure 1. Proposed methodology for the analysis of flood risk zones with fast response rivers.

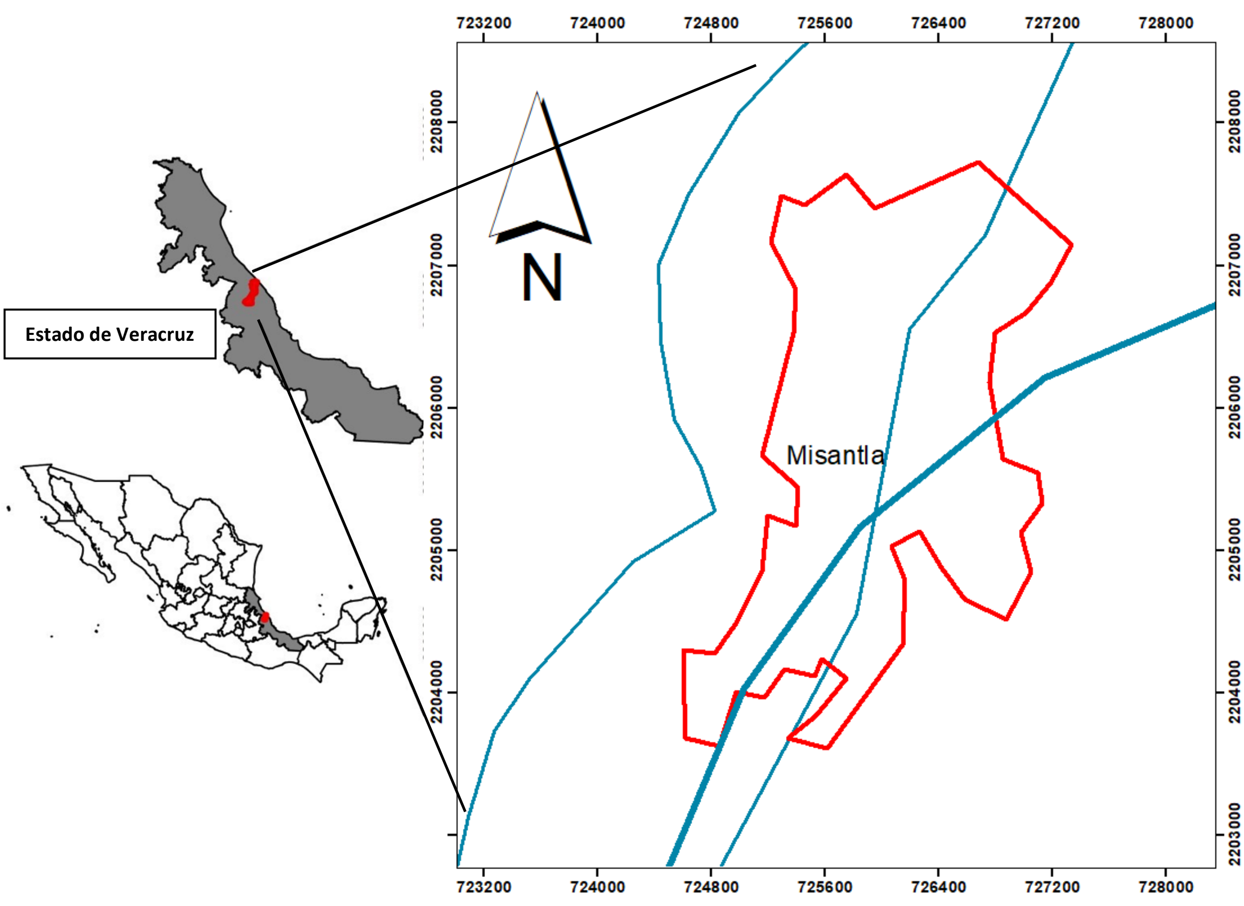

Figure 2. Location of the Misantla River basin (Rodríguez, 2016)

To carry out the hydrographic survey of the Misantla River, field reconnaissance was carried out by visually analyzing the damage caused, and by means of the observation method, logbooks with geographical coordinates were raised using a GPS, simultaneously photographic records of the events were taken and generating establishments in the

Misantla River basin. For the survey, a Topo-bathymetry study was carried out with GPS GNSS RTK equipment with an accuracy of ± 0.02 m, due to the conditions of the River area before hydrometeorological events.

The analysis of the area vulnerable to flooding began with the GIS tool to study the topography of the area, contour lines, urban areas and tributaries. This information is provided by the National Institute of Statistics and Geography (INEGI), this being Step 1 of the proposed methodology. The topographic information is processed in ArcGis (2015), where the Digital Terrain Model (DTM) necessary for the analysis is generated, as shown in Figure 3. In this DTM the relief, heights, the riverbed and the general location of the study area are observed. The GIS application is composed of a spatial database that has been designed and implemented through the geodatabase provided by ArcGIS, which generates independent geographic repositories.

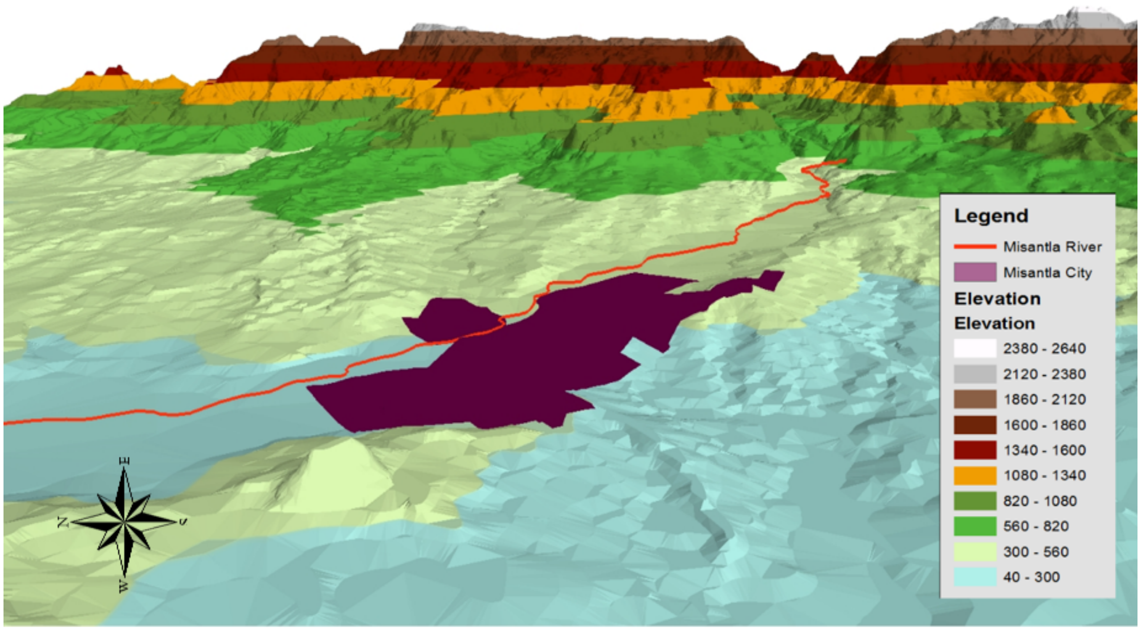

Figure 3. Digital Terrain Model of the Misantla area, through the collection geographic statistical databases (Step 2 of the methodology using ArcGIS).

For the plotting of tributary topographic conditions such as center streamlines, flow path lines, river slopes or shoulders, width and cross sections the HEC-GeoRAS software is used which is a set of procedures, tools and utilities for geospatial data processing in ArcGIS using a graphical user interface (GUI). The interface allows the preparation of geometric data for import and processing of HEC-RAS simulation results. The creation of the DTM import file of the fluvial system (river) is performed in TIN format.

The HEC-GeoRAS extension in ArcGIS allows processing the geospatial information of the river and studying it for export to HEC-RAS. This extension defines the characteristics of the Misantla river, its banks, flow direction and cross sections to study it as shown in Figure 4. The river slopes delimit the main channel and the flood zone. Their position has an impact on the calculation of the roughness of the tributary.

The flow paths indicate the areas where water is anticipated to flow, preferably between the main channel and the two immediate potential floodplains. The flow paths were used in HEC-GeoRAS to determine distances between cross sections in both the main channel and floodplains. The choice of the points at which the cross sections are placed considers the possibility that the spacing of the sections will depend on the uniformity of the geometry, where the greater the uniformity, the greater the distance between the sections. The river section in this study consists of approximately 7 km; the urban area of Misantla; and 168 cross sections were created at an average distance of 30 m between each one (Figure 5).

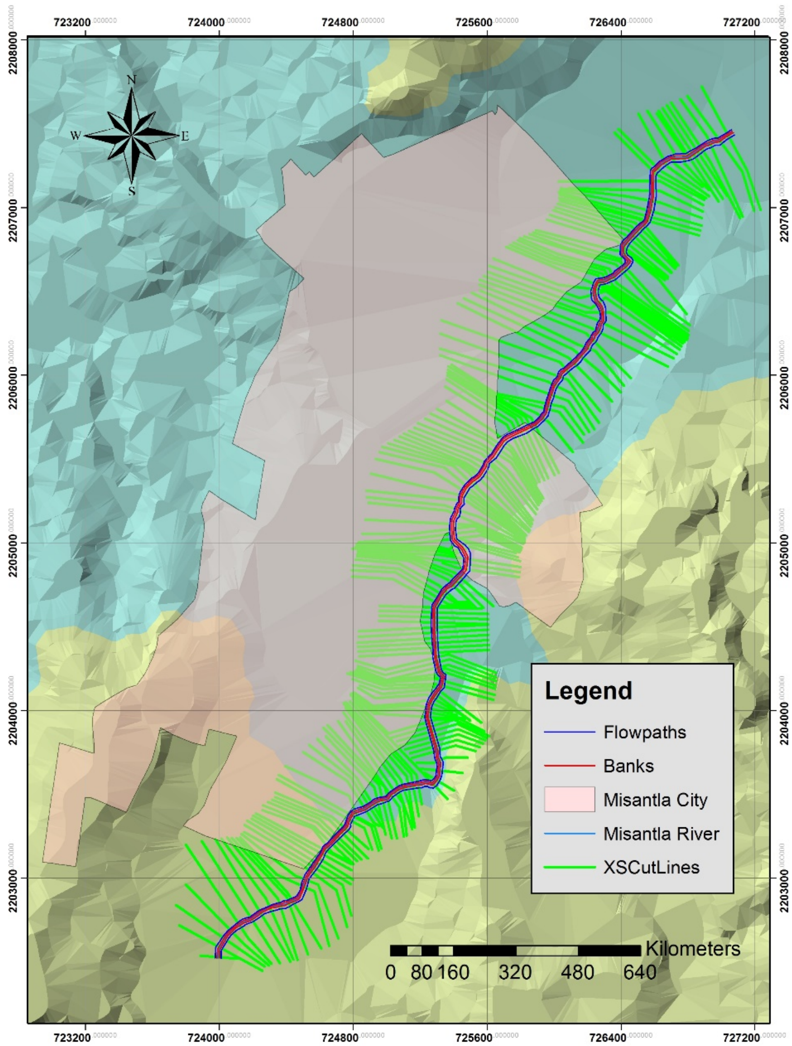

Figure 4. Delimitation of the area to be studied, where the topographic trace of the river under study is constructed and-the transverse traces are observed (Step 3 of the methodology using ArcGIS).

Finally, once the depth and flow velocity maps were obtained, they were processed in ArcGIS software to obtain the risk map. A hydraulic analysis was then performed to obtain the depths and flow velocities. The theoretical basis of the digital tools is presented in Appendix A; while Table S-1 of Appendix B describes the type of material transported by the Misantla river in its riverbank. It can be observed in this Table S-1 that, in the extraordinary floods, cobbles greater than 1 m in diameter are transported. The particle size was determined in the soil laboratory of the Universidad Veracruzana, Faculty of Engineering, Boca del Rio, Veracruz, the samples taken at the study site were transported with current laboratory regulations. These materials prevail up to 30 m depth because of the deep explorations that were carried out in the experimental area. The trawl cobbles have been used in construction for flood protection purposes, including the construction of breakwaters, slope revetments, and other protection works that use cobbles material for their construction.

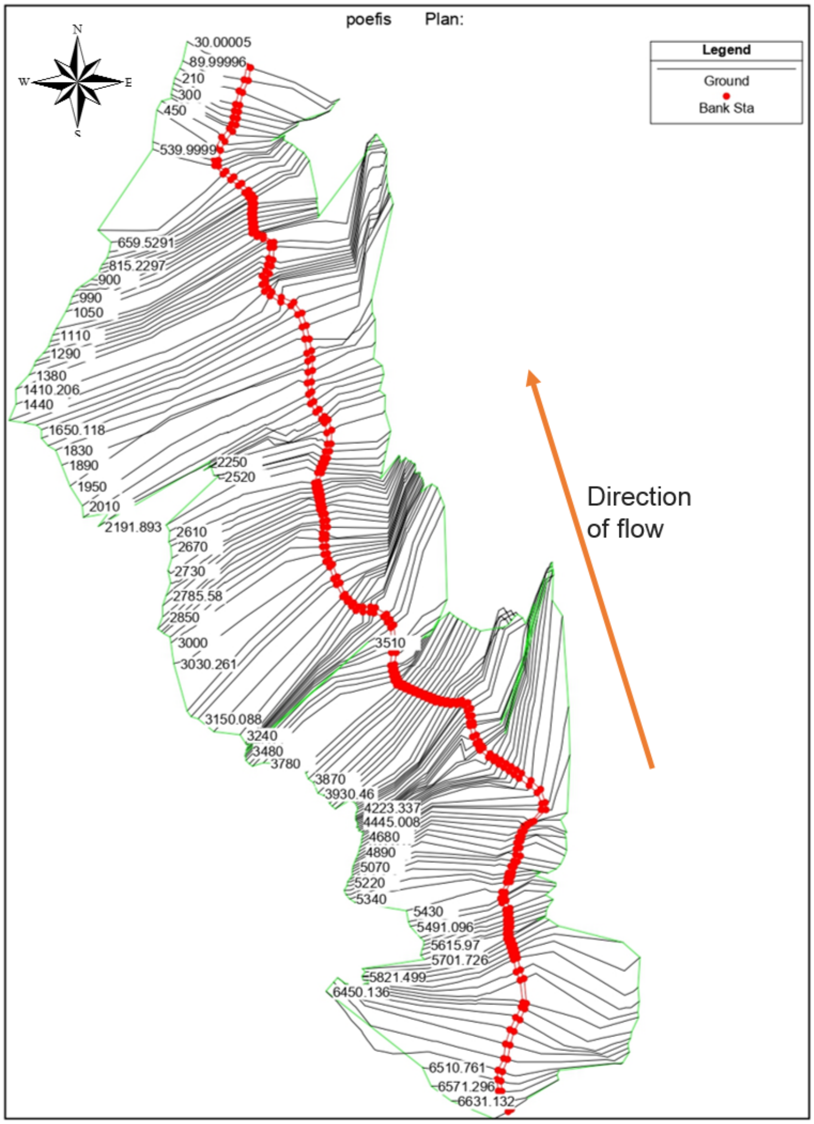

Figure 5. Elaboration of the river profile in the study area with its respective cadenzas (Step 4 of the methodology visualized in Hec-RAS).

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Results and Discussion

With the information on relief, height and riverbed, a depth map was constructed, as shown in Figure 6. This map allows us to visualize the water depths, in meters, reached in different areas of the city, thus determining most of the areas prone to damage by rising water levels. The maximum depth reached in the river was 6.559 m. The location of this maximum recorded depth could be the most likely cause of the bridge breakage due to its proximity to the structure that supported it (Figure 7), and in a similar hydro meteorological event such as the one in 2013, it could repeat the incident if it is not properly designed.

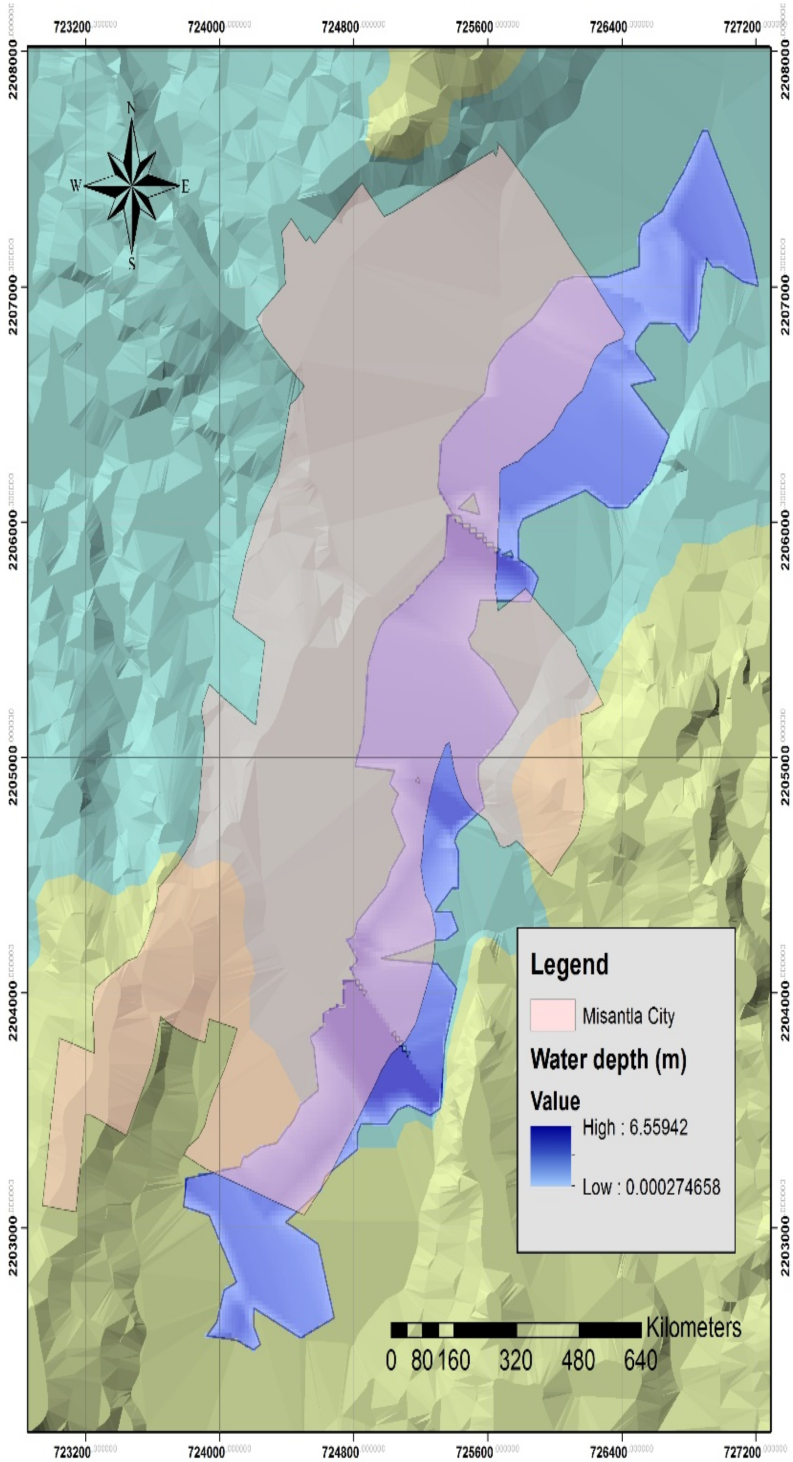

Figure 6. Water level depth map due to flooding effect (Step 5 "Scenario simulation")

Figure 7. Consequences of fast-flowing rivers during the flood season, causing the rupture of a bridge in the Misantla River, generating social isolation among neighboring populations.

Figure 8 shows the velocity map of the water flow, which shows a maximum velocity of 6.985 m/s corresponding to rivers with atypical floods and steep slopes that are not typical of the River; at the height of the city of Misantla, it corresponds to an area with slopes of less than 3% as shown in Figure 9.

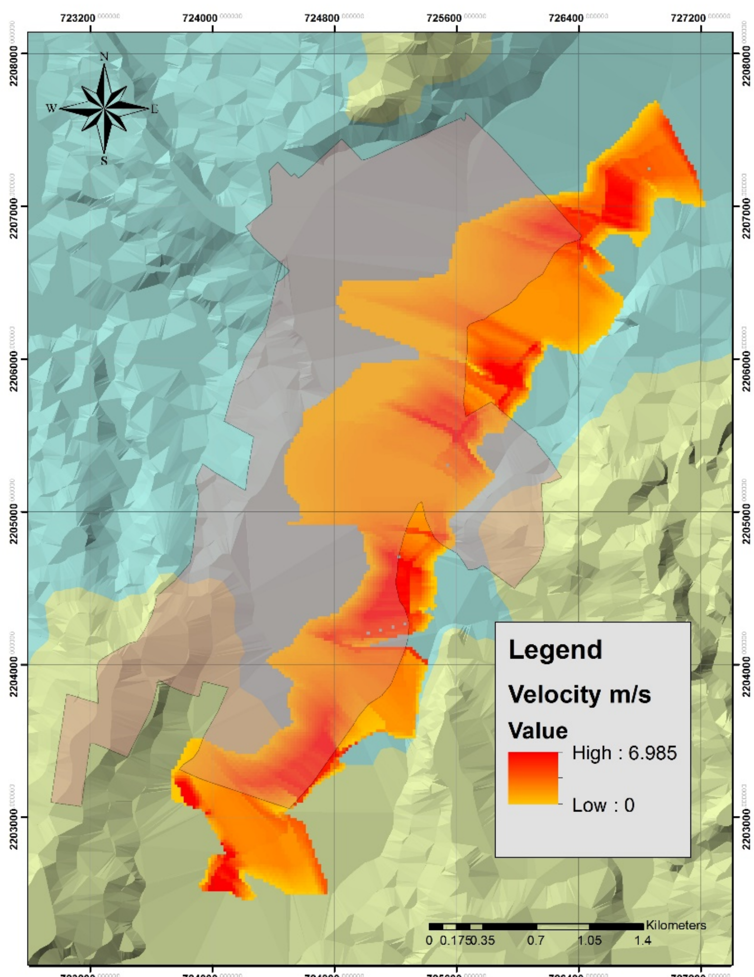

Figure 8. Map of river flow velocities (Step 5 "scenario simulation").

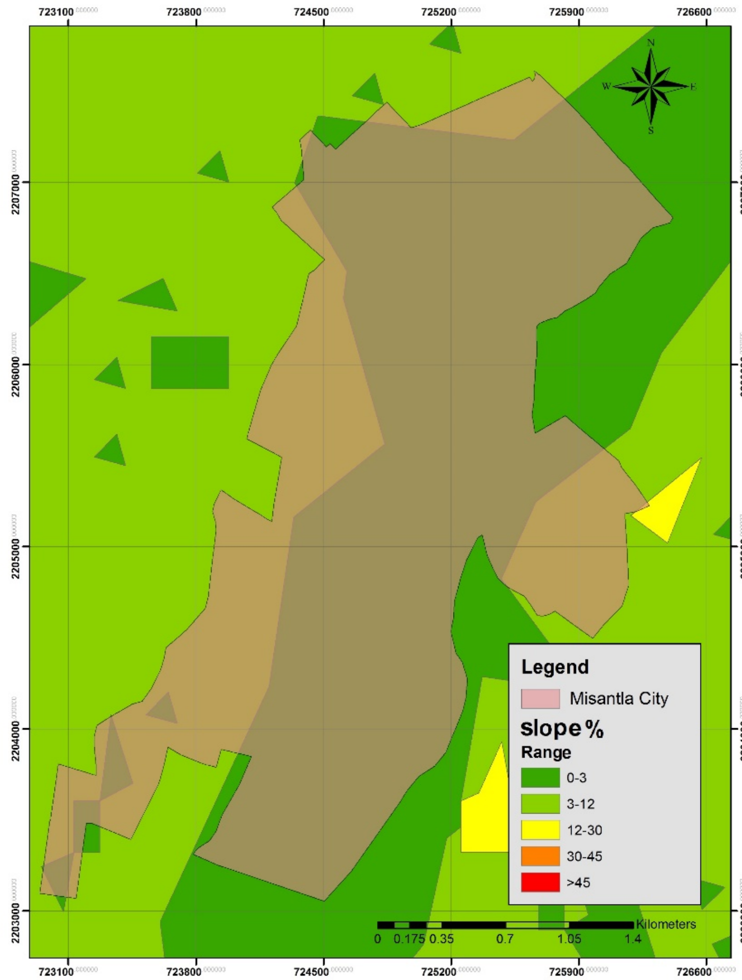

Figure 9. Percentage of slope for the study area (part of DTM Step 2).

Once the flood risk and flow velocity maps had been drawn up, a map of areas vulnerable to flooding was obtained. The thresholds between high, medium and low intensity levels have been defined considering the danger that a given column of water may pose to infrastructure or housing and the lives of the inhabitants (Guillard *et al.*, 1996) Table 1 shows the ranges defined for each flood intensity level.

Table 1. Criteria for determining flood intensity

Intensity levels	**Depth x flow volume (m^3/s) (dynamic flooding)**	**Description**
High	$H*V \geq 2$	High economic damage and danger to the population.
Medium	$0.5 \leq H*V < 2$	Economic and population damages are minor, but not negligible.
Under	$H*V < 0.5$ y $H \geq 0.25$	Slight associated damage, losses in crop areas and animals may occur.

Where H = Height that reaches the river level (m) and V = Velocity of the water current (m/s).
Within the city of Misantla the high risk zones vary from the center of the city, to the lowlands located to the east, potentially affecting more than 10,000 people representing 72.0% of the total population, Figure 10 shows the risk zones in the area of the city of Misantla; the zone in red corresponds to the high intensity of floods, which are those that have the product resulting from the high velocity (Velocity * Depth) is greater than 2.0 m^2 /s. The damages caused by this type of floods are generally of great impact for the economy of a population that does not have economic

resources to attend this type of contingencies. The manifestation of a flood is possible for a community of approximately 2,000 inhabitants located on 1.29 km^2 of riverbank susceptible to this type of risk. The yellow-colored zone corresponds to medium intensity flooding resulting from the high velocity of the river flow (V*H) between 0.5 and 2m^2/s. The impact of a flood in this scenario is likely to occur in 1.89 km^2 of riverbank susceptible to this type of risk. The blue colored zone corresponds to areas with low flood intensity, which are those with V*H less than 0.5 m^2/s. Generally, they are mild, it is expected that the associated damage no loss of life, by early warnings, (although if they can be losses in the areas of cultivation and lives of animals) although they may be losses in crop areas and lives of animals, Prudent in the 1.39 km^2 susceptible to this type of risk.

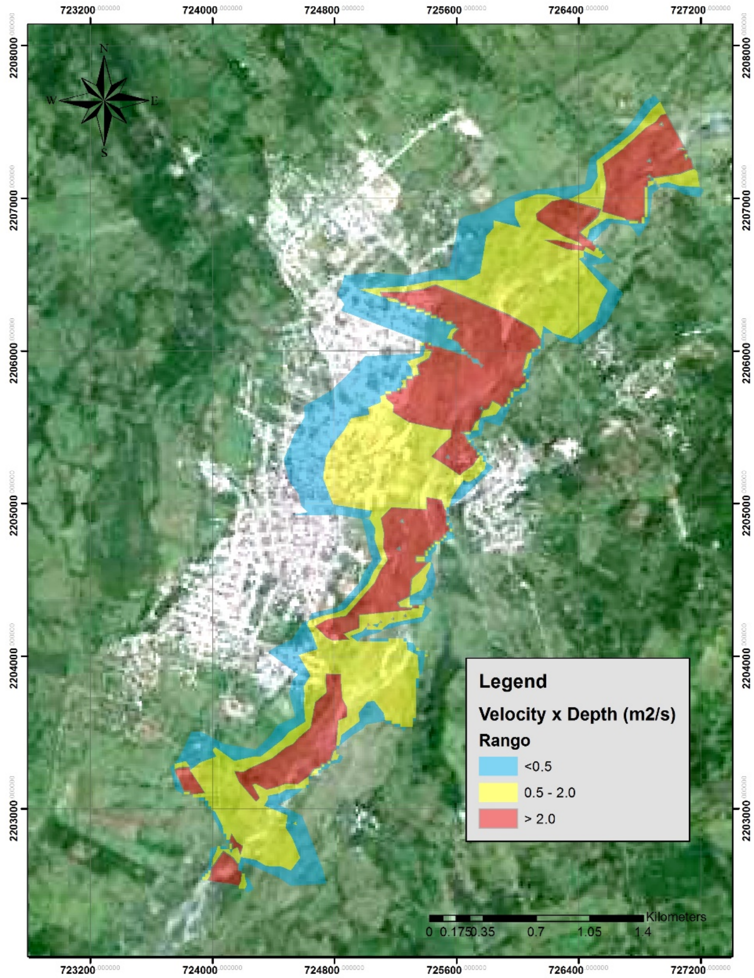

Figure 10. Risk map for the city of Misantla (Step 5 "scenario simulation").

The most common procedures to protect river banks are groynes (Figure 11), marginal revetments and marginal dikes (Erdlenbruch & Grelor, 2017). The main purpose of the mentioned works is to avoid direct contact between the flow with high velocity and the entrainment material (scour material composed of cobbles and gravels) in turn they also help to guide or steer the flow in a desired and convenient direction. In the case study of the city of Misantla, a series of measures have been implemented to prevent flood damage by constructing lateral embankments based on cobbles supported on the river slopes to guarantee adequate flow and prevent erosion, This, together with the proximity of the river's origin in the mountains, due to the effects of rapid response flows, would result in a high-risk zone for the population, which would generate economic investments that are not included in the municipal budgets of developing countries (Combes *et al.*, 2019).

In this regard, studies are needed to help define measures appropriate to the conditions of the site (Macchione *et al.*, 2019) that require particular solutions. On the other hand, digital systems offer the alternative of simulating scenarios and consequently delimiting zones by risk intensity. These simulations show scenarios where damages would be greater than those caused by tropical storm José in 2011 that affected 40.10 km^2 of the municipality of Misantla and left damages of $274,254.93 dollars, or by Hurricane Stan in 2005 that affected 94.60km2 with a cost of $498,125.37 dollars, affecting 7123 inhabitants (Tejeda, 2006; Rodríguez, 2020). Figure 11 shows the construction of a breakwater near the Misantla bridge in order to buffer and divert the river current, the height of the bridge is 5.0 m and the results of the analysis show a maximum water height of 6.559 m, which is insufficient for maximum flooding events, according to interviews with the city's inhabitants, the river enters the urban zone at a distance of 5.0 km before the bridge, so the infrastructure is protecting the roadway but not the population.

Figure 11. Breakwaters built near the bridge to protect it from the river current.

Conclusions

In this article, a GIS-supported digital methodology has been proposed to simulate flood scenarios in urban populations in shallow rivers with rapid response. The digital methodology proposed in this article uses the city of Misantla, Mexico, as a case study. The digital methodology generates a spatial map of flood risk vulnerability that describes an area of 4.58 km^2 of the river bank affecting 57.3% of the total area of the city (approximately 8.0 km^2). In another scenario, an area of 1.39 km^2 is in a high-risk zone representing 17.4% of the urban area.

Knowledge of the flood zones of an urban area provides information on possible flood events in order to design strategies and protection structures that minimize the impact of damage from such events. In this sense, it is important for future work to simulate scenarios that evaluate the design of protection structures under conditions of possible natural flood events of the magnitude reported in this study.

Hydraulic simulation in HEC-RAS (US Army Corps of Engineers, 2010) is based on deterministic differential equations, which when solved allow predicting the dynamics of water levels in extreme floods, defining flood levels through transverse profiles. This is possible by simulating probable scenarios of the behavior of water resources dynamics and characteristics of sections: variable wetlands with any geometry; different types of surface roughness for certain parts of the wetland profile; different water depths and with variable flow in conditions of sub-critical or super-critical flow regime with hydraulic effects due to natural or artificial transverse obstacles.

Acknowledgments and Funding: Thanks to the Consejo Nacional de Ciencia y Tecnología (CONACYT) for the financial support for the development of this research and to the Instituto Nacional de Estadística y Geografía (INEGI) for the information provided for this article. Appendix A. Theoretical foundation of HEC-RAS.

Author contributions: S.A.Z.-C. and L.C.S.-H.: methodology; J.S.L. and S.R.: software; M.S.-H.: validation, graphs and figures; J.S.L. and S.R.: formal análisis; S.A.Z.-C. and L.C.S.-H.: investigation; L.C.S.-H., S.A.Z.-C., G.N., M.S.-H.: resources; L.C.S.-H.: writing—original draft preparation; L.C.S.-H., S.A.Z.-C.: writing—review and editing; S.A.Z.-C., S.R., J.S.L., and S.A.Z.-C.: visualization; L.C.S.-H. and S.A.Z.-C.: supervisión; S.A.Z.-C. and L.C.S.-H.: project administration; L.C.S.-H.: funding acquisition; L.C.S.-H. and S.A.Z.-C.

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Supplementary Material

Appendix A. One-dimensional HEC-RAS model.

In the one-dimensional HEC-RAS model, the mass and time conservation equations are solved by a system of linear equations using Preissman's second-order scheme; the software is based on the solution of the energy equation, in which friction losses are evaluated by the Manning equation (Dyhouse, 2003), and the contraction and/or expansion losses are proportional to the change in velocity heads. For situations of varying rapid discharge, such as at the inlet of water supply or hydraulic heads, HEC-RAS also uses the momentum equation to find the solution. The software is based on the solution of the momentum equation:

$$P_2/\gamma_2 + Z_2 + (a_2 V_2^2)/2g = P_1/\gamma_1 + Z_1 + (a_1 V_1^2)/2g + h_f \quad \textbf{(1)}$$

where a is the correction factor; P is the pressure; γ is the specific weight; h_f is the losses due to friction between the points; g is the acceleration of gravity; V is the flow velocity; and Z is the elevation.

Friction losses are evaluated by Manning's equation:

$$I = (n^2 Q^2)/(A^{10/3} P^{4/3}) \quad \textbf{(2)}$$

where n is the Manning's roughness coefficient; Q is the waste (ft^3/s, m^3/s); A is the flow section area (ft^2, m^2); and P is the wetted perimeter (ft, m).

HEC-RAS also uses the momentum equation to find the solution:

$$\partial Q/\partial t + \partial QV/\partial x + gA(\partial z/\partial x + S_f) = 0 \quad \textbf{(3)}$$

where S_f is the average transport equation.

The next step consists of the simulation in the HEC-RAS program with the data imported from ArcGIS. Once the geospatial characteristics of the river are given, the characteristics of the design discharge are defined, which in this case uses the maximum discharge recorded during 1995, calculated at 2,250 m^3/s in the city of Misantla.

Appendix B. Material transported on the Misantla river bank.

Table S-1 shows the results of the soil particle size test, with an average of 82.3% cobbles, 10.5% gravels, 6.3% sands and 1.0% fine material.

Table S-1 Particle size test results.

Study	Depth, m	% Stones	% Gravel	% Sand	% Fine material (clays and silts)	Description
PCA-1	0.00 - 100	66.5	22.4	11.0	0.1	Gravel and sand loosely packed slopes
	1.00 - 3.50	93.5	4.5	1.5	0.4	Densely compacted stone
PCA-2	0.00 - 0.60	90.1	4.1	4.8	1.0	Gravel and sand loosely packed slopes
	0.60 - 3.50	97.6	1.4	0.8	0.2	Densely compacted stone
PCA-3	0.00 - 1.50	53.8	25.1	18.1	3.0	Gravel and sand loosely packed slopes
	1.50 - 3.50	92.1	5.4	1.4	1.1	Densely compacted stone