Understanding the Influence of Vegetation on Urban Open-Channel Flow: A Numerical Modeling Approach in Monterrey, Mexico

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Abstract:

Flooding poses a persistent threat to urban areas, prompting the use of mathematical modeling to understand flow dynamics and delineate flood zones. Integrating vegetation into hydraulic models is crucial for assessing its effects on flow characteristics, sediment transport, and channel morphology. The Santa Catarina River in Monterrey, Mexico, experiences irregular water levels, leading to unchecked vegetation growth during dry seasons and vegetation loss during extreme weather events like hurricanes. This study utilized two hydraulic models, employing Digital Elevation and Surface Models alongside land use classifications and hydrological data from Hurricane Alex in 2010, to evaluate vegetation's impact on flood simulations. The results reveal significant changes in flood patterns due to vegetation, shifting the flood zone towards residential-commercial areas. Maximum depths increase from 10.70 to 16.78 meters, and affected areas deepen from 2 to 4.37 meters with the vegetation-inclusive model. These findings underscore vegetation's pivotal role in shaping urban flood pathways and advocate for integrating natural and human elements in flood risk management strategies. Future research avenues could explore socio-economic implications and evaluate cost-effective mitigation measures for diverse flooding scenarios.

Keywords: Hydrodynamic model, Flood, Runoff, Hazards, Risk, Susceptibility.

1. Introduction

Flooding is a constant hazard in many cities. To prevent and mitigate flooding-related damage, it is necessary to simulate the dynamic of the flow within the environment and define the possible flood zones. Incorporating vegetation in hydraulic models is pivotal for understanding its impact on flow characteristics, sediment transport, and channel morphology.

This research, which investigates the impact of vegetation on flood simulations in the Santa Catarina River, can bring about significant benefits in urban flood risk management. Urban flood simulation models are essential in urban planning and risk management, offering crucial insights into flood dynamics and risk assessment. By simulating various flood scenarios, these models help planners and decision-makers understand potential flood behaviors and identify vulnerable areas. They enable the assessment of flood risks under different conditions, such as varying rainfall intensities and land use changes, thereby informing the development of effective mitigation strategies. Furthermore, these models support the design of resilient infrastructure, guiding the allocation of resources to areas most at risk. Through their predictive capabilities, urban flood simulation models play a vital role in enhancing urban areas' preparedness and response strategies, ultimately protecting lives and property.

Changes in vegetation cover significantly impact flow patterns in open urban channels by altering water velocity, increasing surface roughness, and influencing sediment transport. Vegetation density, stem diameter, vegetation length, and flow depth all affect flow resistance, resulting in energy loss, momentum exchange, and shear stress distributions in compound channels but reduced conveyance capacity (Urgeghe et al., 2021; Khuntia et al., 2023). The presence of vegetation can decrease the flow velocity and change the velocity distribution in the vegetated zones compared to the free-flow zone (Bauer et al., 2022). However, depending on density and arrangement, vegetation may impede water flow, causing localized accumulation (i.e., an accumulation that can act as an obstacle) and potentially increasing upstream flooding levels.

Flood simulations use topography as the foundational basis, which involves removing temporary surface obstacles like vegetation. This approach allows for a more accurate representation of the terrain's natural contours and hydrological characteristics, enabling the simulation models to predict water flow and accumulation patterns more precisely. By eliminating transient elements like vegetation, which can change over time and seasonally, the models focus on the permanent features of the landscape. Topography-based models ensure that these simulations' flood risk assessments and mitigation strategies are based on the stable, underlying geography. However, it is well known that vegetation can represent a significant obstacle in the actual river flow.

The Santa Catarina River in Monterrey, Nuevo León, has been pivotal in the city's urban landscape since its channelization in 1952. This channelization has profoundly influenced the urban-river dynamic, emphasizing the complications arising from the improper use of the riverbed as a public space. Following 2010, there have been significant environmental regeneration efforts, which have brought notable ecological benefits, especially in terms of climate change mitigation. These efforts aim to mitigate the risks associated with the river's potential loss, underscoring the necessity of sustainable practices for its long-term preservation. As detailed by Vega (2023), this historical and urban context makes the Santa Catarina River an exemplary area for studying how vegetation impacts the river's flow and contributes to flooding risks.

This study aims to evaluate the impact of vegetation on flood simulations in the Santa Catarina River. The experiment was

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carried out by utilizing two distinct hydraulic models: one based on a typical Digital Elevation Model (DEM) and the other by a Digital Surface Model (DSM) with incorporated manually digitized vegetation, along with land use classifications and hydrological data from Hurricane Alex in 2010. By comparing simulations with and without vegetation, the study seeks to quantify the influence of vegetation on flood patterns, depths, and affected areas.

1.1 Study area

The Santa Catarina River in Monterrey, in northern Mexico (Fig 1), initially used for civil infrastructure such as parking lots, sports fields, and mobile shops due to perennial water availability, underwent a notable transformation following the devastation caused by Hurricane Alex in 2010, which swept away all artificial structures. Consequently, a political decision was made to preserve it as a living river (Fig 2). Currently, it boasts a diverse array of shrubs and trees, some towering up to 25 meters in height, symbolizing a return to its natural state and serving as a testament to its resilience against human alterations and natural disasters (More information can be read in Aguilar-Barajas & Ramírez, 2019). Managing these fluctuations requires strategies that balance environmental preservation with urban infrastructure resilience.

This river has a history shaped by multiple extreme precipitation events. Notable floods, such as those in 1909, and 1933, and 1988 caused by Hurricane Gilberto, have left significant marks on the city and its infrastructure. Recent meteorological events, including hurricanes Emily in 2005, Alex in 2010, Patricia in 2015, Tropical Storm Beta in 2020, and Hurricane Hanna in 2020, have underscored the region's vulnerability to extreme weather phenomena. In response to the need for better flood control, the Rompepicos Dam was completed in 2013. This infrastructure has played a crucial role in flood management by regulating the river's flow and mitigating downstream risks. The Rompepicos Dam has been pivotal in controlling the effects of these events, significantly reducing the risk of flooding in Monterrey and its surroundings.

Actually, apart from vegetation, the riverbed of the Santa Catarina River is primarily composed of Quaternary alluvial sediments, predominantly sandy gravels. Additionally, some riverbed sections are covered with metallurgical waste from the former steel industry and urban landfill debris (Martínez-Quiroga et al., 2021).

1.2 Flooding simulations

In San Pedro Garza García, a municipality through which the Santa Catarina River flows, recent flood hazard assessments indicate a shallow risk, with less than a 1% chance of severe flooding over the next decade, equivalent to a return period of approximately 1 in 1000 years (Global Facility for Disaster Reduction and Recovery, 2023). The reported shallow risk contrasts with the findings of Aguilar-Barajas et al. (2019), which report that flash floods triggered by Hurricane Alex in 2010 caused 15 fatalities in the Monterrey Metropolitan Area, while Hurricane Gilbert in 1988 resulted in approximately 225 deaths and the historic flood of 1909 caused reputedly over 5,000 fatalities. Despite improvements in resilience, Aguilar-Barajas et al. highlight ongoing challenges related to fragmented national water governance and the need for continued effective adaptation strategies.

Recent flood modeling studies in the Santa Catarina River watershed highlight diverse approaches to understanding flood dynamics. Stella (2023) utilized HEC-RAS for a two-dimensional simulation during Hurricane Alex in 2010, using multisensor precipitation data and calibrating the model with observations from the Cadereyta Hydrometric Station. Similarly, Cazares-Rodriguez (2016) applied HEC-HMS and tRIBS to evaluate flood mitigation strategies, simulating various scenarios to assess the impacts of hydraulic infrastructure. These studies underscore the utility of HEC-RAS and HEC-HMS in novel watershed contexts. In contrast, the present study focuses on a local scale, modeling only the urban section of the Santa Catarina River and incorporating vegetation effects using the DSM model. This localized approach provides a higher-resolution perspective on flood dynamics than previous models.

2. Methodology

This study used two hydraulic models through IBER to assess vegetation's impact on flood simulations following the workflow shown in Fig. 3. We conducted two hydraulic modeling scenarios: one considering bare terrain, utilizing a digital elevation model, and the other incorporating vegetation cover.

The IBER software is an advanced hydraulic and hydrological modeling tool to simulate river and channel behavior. Developed by a collaboration between GEAMA (Universidade da Coruña), Flumen (Universitat Politècnica de Catalunya), and EPHYSLAB (Universidade de Vigo), It applies the finite volume method to solve the shallow water equations providing detailed insights into water depth and flow velocity across various scenarios (García-Feal et al., 2017). IBER relies on fundamental mathematical principles, including the Saint-Venant equations for open channel flow dynamics and advection-diffusion equations for pollutant transport. These equations govern mass, momentum, and energy conservation and enable accurate simulations of flood events and flow dynamics (Prado-Hernández et al., 2019).

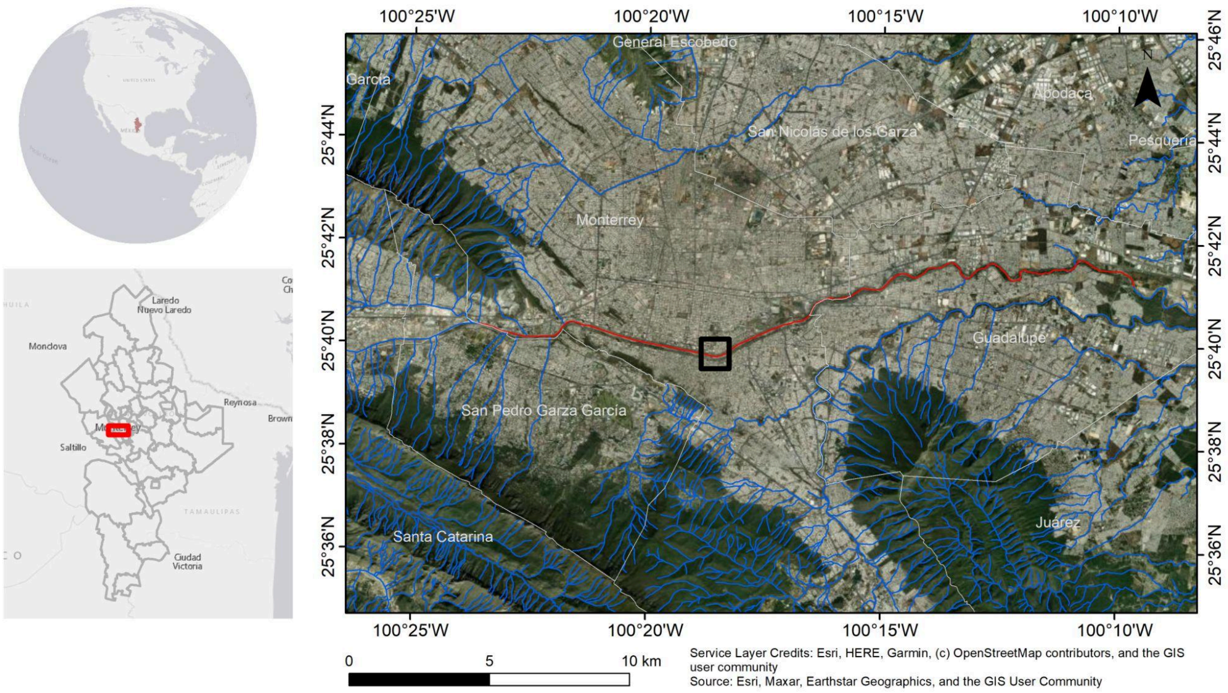

Figure 1. Location map of the Santa Catarina River in Monterrey, Mexico. The red line indicates the section processed in the hydraulic modeling. Inset 1 (black box) highlights are explained in Figure 2.

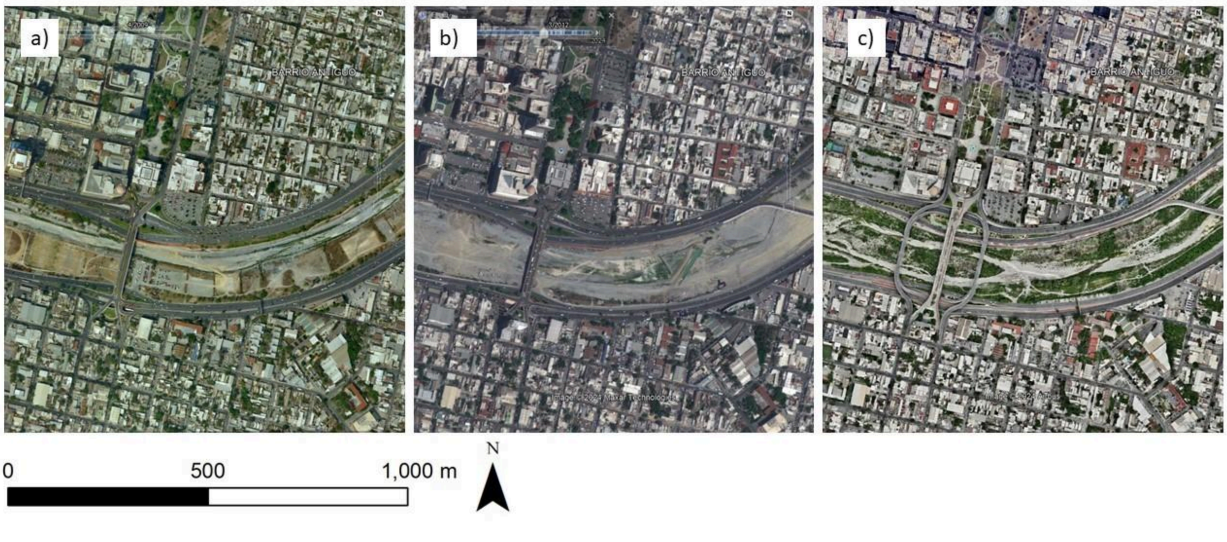

Figure 2. Temporal evolution of the inset 1 (black box in figure 1) in the Santa Catarina River. (a) Pre-Hurricane Alex (year 2009), showing the presence of sports fields and a paved parking lot. (b) Post-Hurricane Alex (2012) illustrates the complete removal of all infrastructure. (c) Actual year (2024), depicting the river as a restored living ecosystem.

2.1 Hydrological parameters

Both models used a peak flow rate of 2956 m3/s, equivalent to that recorded during Hurricane Alex in 2010 (Ramírez-Serrato et al., 2016). Model parameterization was completed within a timeframe of 40400 s.

2.2 Roughness parameters

Manning's number, or roughness coefficient, is a crucial parameter in hydraulic modeling that describes the frictional resistance between a fluid and the channel bed. It plays a critical role in determining how water flow is affected by the roughness of the surface over which it travels, influencing both flow velocity and depth.

This study determined soil roughness through an automated classification of land cover types using Sentinel-2 satellite imagery with a spatial resolution of 10 meters. The classification was performed using the Maximum Likelihood method, which enables the accurate categorization of different land cover types. Each identified land cover class was then assigned a Manning's roughness coefficient based on the default values provided by the Iber model for each category.

2.3 Topography digital models

The DEM and DSM, with a 5-meter resolution, were obtained via LiDAR techniques from the INEGI government web platform. Bridges were eliminated from both models by digitized polygons in Google Earth.

One model employed a Digital Elevation Model (DEM), portraying only terrain topography.

The second model used a Digital Surface Model (DSM) integrating manually digitized vegetation from Google Earth imagery (2020). This vegetation was mapped through manually digitized polygons, with assigned heights of 3m for shrubs and 15m for trees emulated. These polygons were rasterized and added as patches to the DSM.

3. Results

The findings highlight significant changes in flood patterns attributed to vegetation. Its presence alters the flow, shifting the flood zone towards a southwest residential commercial area. Compared to the 10.70-meter maximum depth in the DEM-based hydraulic model (Fig. 4a), the DSM integrated model has a maximum depth of 16.78 meters (Fig. 4b). Additionally, the consistently affected area deepens from 2 meters to 4.37 meters when considering the vegetation-inclusive DSM-based approach. Reported discharge from the DEM model was 2590 m3/s vs. 2800 m3/s from vegetation-inclusive DSM.

The results from both models, one based on the DEM and the other incorporating vegetation using the DSM, reveal significant differences. The DSM-based model reports the highest inundation depth at 16.78 units, while the DEM-based model records the highest velocity of 12 m/s. Additionally, the DSM-based model shows the most extensive inundation coverage of 13.43 km2.

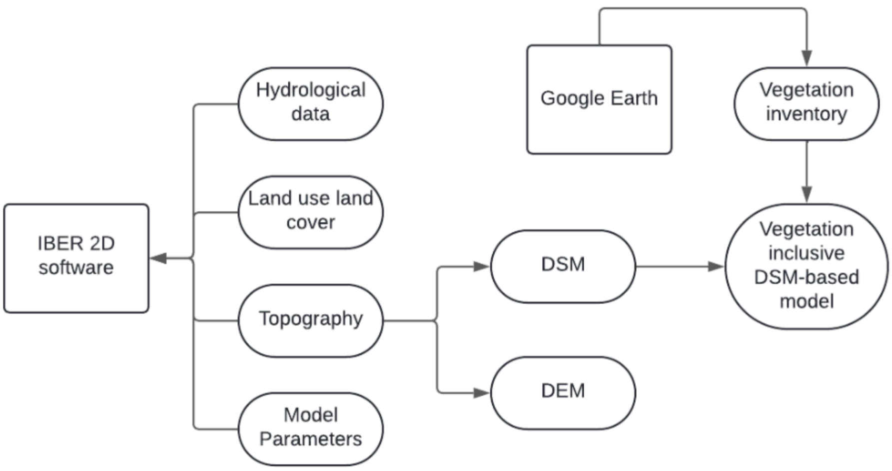

Figure 3. Workflow used with IBER 2D software.

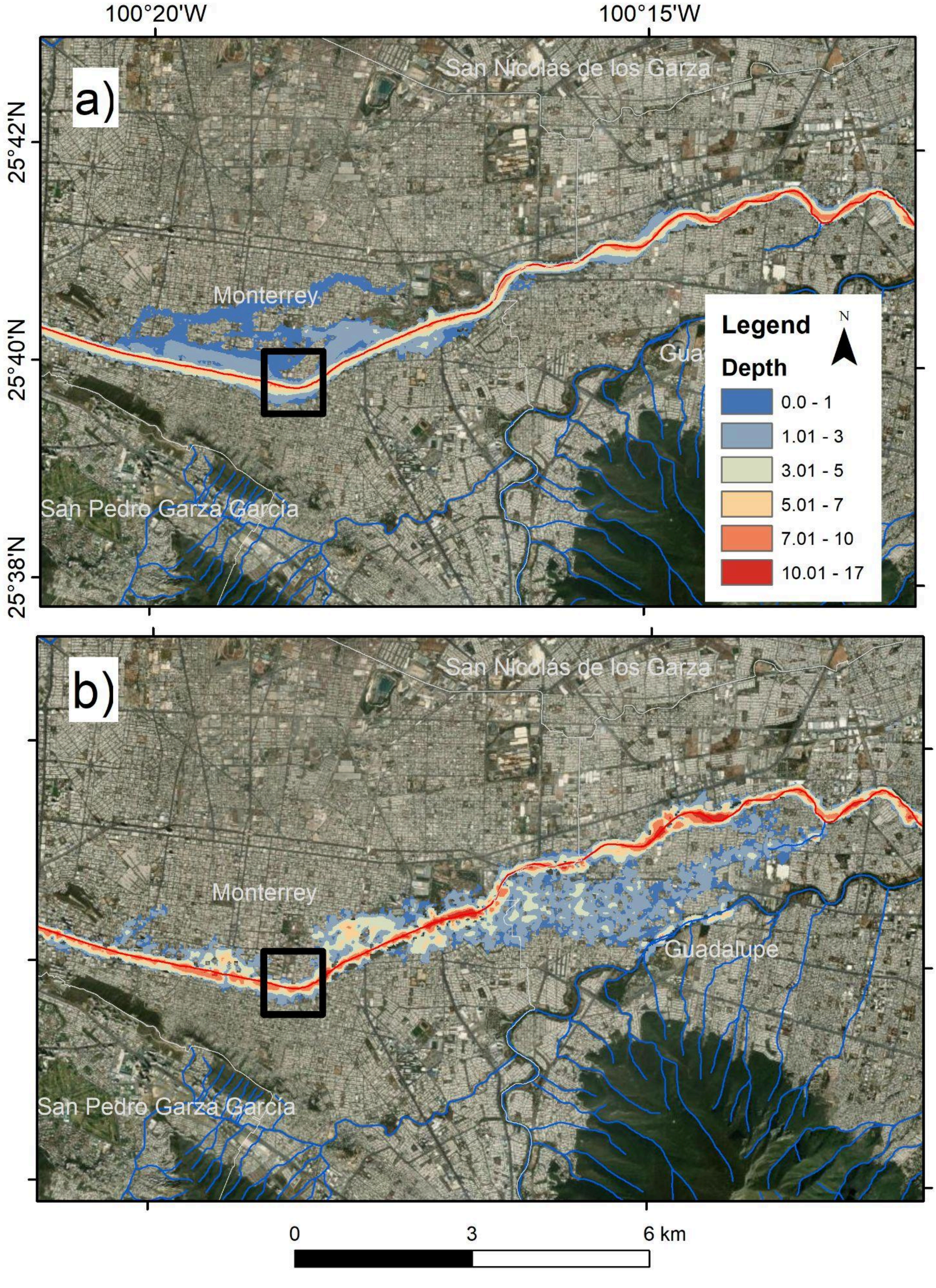

Figure 4. Flood simulation results. Above (a) Flood simulation with the DEM-based hydraulic model and below (b) Flooding simulation with DSM integrated model.

4. Conclusion

According to the modeling outcomes, vegetation significantly influences the watercourse dynamics. While there is a delayed effect on flow velocity, there is also an observed increase in inundation area and depth, consequently extending flood morphology towards residential areas. Both models illustrate considerable and risky flood morphology for some urban areas in Monterrey city, underscoring the necessity for mitigation measures extending beyond routine river maintenance, such as implementing channel deepening strategies.

In this work, vegetation is simulated as fixed obstacles, and its possible drag is not simulated. However, it is essential to note that the dragging of vegetation and sediments could trigger debris flow scenarios, so these scenarios must also be simulated.

These avenues present promising trajectories for further studies, offering insights into the socio-economic and financial implications of diverse flooding patterns in urban settings.

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