Ambiente & Água - An Interdisciplinary Journal of Applied Science
ISSN 1980-993X – doi:10.4136/1980-993X
www.ambi-agua.net
E-mail: ambi.agua@gmail.com

Modeling Alex Hurricane: flood map simulation applying Multisensor grid precipitation, Monterrey, Mexico

ARTICLES doi:10.4136/ambi-agua.2911

Received: 23 Jan. 2023; Accepted: 31 May 2023

Juan M. Stella

Department of Civil and Environmental Engineering. Lamar University,
Beaumont, TX, USA. E-mail: jstella@lamar.edu

ABSTRACT

A simulation was carried out in the Santa Catarina River watershed, located in the State of Nuevo Leon, Mexico, to study flood patterns and velocity maps during the occurrence of Hurricane Alex in June-July 2010. To conduct this simulation, a two-dimensional model of the Santa Catarina River Watershed was employed using the HEC-RAS software. The model was driven by Multisensor grid precipitation data as input. Land cover and soil layers were utilized in order to obtain various parameters within the watershed, such as Curve Number, Manning Number, Abstraction Ratio, Infiltration Rate, and Percent of Impervious Land. The simulated water levels were calibrated by comparing them with observed values at the Cadereyta Hydrometric Station, which is located near the city of Monterrey. The utilization of the HEC-RAS two-dimensional model combined with Multisensor grid precipitation demonstrates that this particular model is easy to set up and is user-friendly. Moreover, the model exhibits stability and possesses the ability to accurately simulate flood patterns and velocity maps within the watershed.

Keywords: Floodmap, HEC-RAS 2D, Mexico, Monterrey, MRMS-QPE.

Modelando Alex Hurricane: simulação de mapa de inundação aplicando grade de precipitação Multi-sensor, Monterrey, México

RESUMO

Foi realizada uma simulação na Bacia Hidrográfica do Rio Santa Catarina, localizada no Estado de Nuevo Leon, México, para estudar padrões de inundação e mapas de velocidade durante a ocorrência do furacão Alex em junho-julho de 2010. Modelo da Bacia Hidrográfica do Rio Santa Catarina foi empregado usando o software HEC-RAS. O modelo foi conduzido por dados de precipitação da grade Multi-sensor como entrada. A Cobertura do Solo e as Camadas de Solos foram utilizadas para obter vários parâmetros dentro da bacia hidrográfica, tais como número de Curva, número de Manning, Taxa de Abstração, Taxa de Infiltração e Porcentagem de Terra Impermeável. Os níveis de água simulados foram calibrados comparando-os com os valores observados na Estação Hidrométrica Cadereyta, localizada perto da cidade de Monterrey. A utilização do modelo bidimensional HEC-RAS combinado com a precipitação em grade Multi-sensor demonstra que este modelo específico é fácil de configurar e fácil de usar. Além disso, o modelo apresenta estabilidade e possui a capacidade de simular com precisão padrões de inundação e mapas de velocidade dentro da bacia hidrográfica.

Palavras-chave: HEC-RAS 2D, mapa de inundação, México, Monterrey, MRMS-QPE.

1. INTRODUCTION

The Monterrey Metropolitan Area (MMA), situated in the State of Nuevo Leon, Mexico, has a documented history of experiencing flooding, with records dating back to 1612 (Ferriño-Fierro *et al.*, 2010; Fuentes-Mariles *et al.*, 2014). Hurricanes have hit the area, experiencing significant damages causing significant human and material losses, including Hurricanes Beulah in 1967, Gilberto in 1988, Emily in 1995 and Alex in 2010. The most significant disaster to date occurred in 1909, when a flood resulted in between four and six thousand fatalities and more than 200 hectares impacted (Ferriño-Fierro *et al.*, 2010; Fuentes-Mariles *et al.*, 2014). In addition to the hydro-meteorological dangers, the MMA faces increased exposure to these phenomena due to unregulated urban growth. The expansion of urban areas into vulnerable zones has led to persistent flooding problems along the Santa Catarina River and its banks. The rapid urbanization of Monterrey City exacerbates the issue by concentrating rainwater, as urban surfaces with low permeability hinder water infiltration and accelerate surface runoff (Ferriño-Fierro *et al.*, 2010; Fuentes-Mariles *et al.*, 2014).

Pasch (2010) and González-Alemán *et al.* (2018) stated that Hurricane Alex was a rare event: the most intense tropical cyclone in the North Atlantic since 1938, recorded as a Category 2 hurricane. Hurricane Alex, which occurred in 2010, caused significant damage to bridges and houses, and deaths were reported (Ferriño-Fierro *et al.*, 2010; Fuentes-Mariles *et al.*, 2014). The interaction between tropical moisture and orographic barriers in the Sierra Madre Oriental caused widespread rainfall, with an accumulated precipitation of 890 mm recorded at La Estanzuela Station in the MMA from June 28t^{h} to July 2nd, 2010. Flash floods triggered by Hurricane Alex caused 22 fatalities in the MMA and an estimated loss of US$2 billion (Sánchez-Rodríguez and Cavazos, 2015).

After Alex Hurricane, Aguilar-Barajas *et al.* (2019) analyze the process of building resilience to flash floods in the MMA. The study notes that the MMA resilience-building efforts are conditioned by the nature of the hazard, which is infrequent but liable to cause significant damages, and contingent upon the city's socioeconomic and institutional local context (Aguilar-Barajas *et al.*, 2019). This local context is embedded in a highly fragmented national water governance architecture that lacks inter-institutional coordination, which has limited the city's adaptive responses to flood hazards. Aguilar-Barajas *et al.* (2019) identifies several challenges that the MMA faces, that include the need for sustained funding, political support, collaboration and communication among stakeholders, and a more integrated and coordinated national water governance architecture.

Ramírez-Serrato *et al.* (2016) conducted a study to assess the impact of the historical changes in land use in the Santa Catarina River watershed. A two-dimensional hydraulic modeling of the Santa Catarina River was conducted using a Digital Surface Model obtained through a photogrammetric reconstruction technique of old aerial photographs from the 40s, 50s, and 70s of the MMA. This study also involved hydrological modeling of precipitation data, the projection of historical events such as the channelization of the Santa Catarina River in 1950, the possible effect of Hurricane Beulah in 1967, and other extraordinary events, showing the change in floodplain coverage over time along the length of the Santa Catarina River. Ramírez-Serrato *et al.* (2016) suggest that the channeling of the Santa Catarina River carried out in past decades was beneficial. The findings also highlight the importance of considering historical data when studying the impact of urbanization on the natural environment. Overall, the study provides insights into the changes in the Santa Catarina River and its floodplain coverage over time, and its implications for the city's infrastructure and urban planning (Ramírez-Serrato *et al.*, 2016).

Cázares-Rodríguez (2017) conducted a study to find a flood mitigation strategy of the Santa Catarina River watershed that was suggested by stakeholders during a participatory workshop. The flood mitigation strategy is evaluated using two hydrological models: HEC-HMS and tRIBS. The proposed strategy involved the construction of additional hydraulic infrastructure alongside the existing flood controls in the Santa Catarina River watershed. To evaluate the effectiveness of this strategy, three scenarios were simulated: 1) The impact of the existing flood controls in the watershed; 2) Implementation of a large dam similar to the Rompepicos Dam; and, 3) Addition of three small detention dams. The study encountered several challenges, including limitations in model calibration due to the scarcity and uneven temporal resolution of streamflow gauges. Additionally, the mountainous and steep terrain of the watershed revealed that spatial variations, particularly changes in slope, played a significant role in the complex hydrological processes of the Santa Catarina River watershed. Topographic attributes were found to strongly influence the runoff mechanisms in the area.The results indicated that the implementation of the Rompepicos Dam contributed to a reduction in the flood peak at the watershed outlet by approximately 13.7-15% and, the justification for a costly investment in a large structure designed specifically for extreme events can be attributed to the presence of the MMA, which stands as one of the most critical cities in the country and a key contributor to its economic development (Cázares-Rodríguez, 2017).

Since the late 20th century, there has been a focus on creating new systems and applications to meet the demand for quantitative precipitation estimation. These involve multiple overlapping remote sensing observations or radars, as well as Numerical Weather Predictions (NWP) (Droegemeier *et al.*, 2002; Kelleher *et al.*, 2007). Currently, the National Oceanic and Atmospheric Administration (NOAA, 2022) uses the Multi-Radar Multi-Sensor - Quantitative Precipitation Estimation (MRMS-QPE) system of grid precipitation, which provides real-time, multisensor precipitation estimates. This system uses a grid mesh of 1 km with a 5-minute time step and has minimal time lag from the actual event. The MRMS-QPE grid precipitation has been operational since 1997, when the NEXRAD network was deployed (Zhang *et al.*, 2013; NOAA, 2022; Kitzmiller *et al.*, 2013) and is used to provide input to hydrologic models (Zhang *et al.*, 2013; NOAA, 2022; Kitzmiller *et al.*, 2013). The Iowa Environmental Mesonet (IEM, 2022) collects environmental data, including precipitation, solar radiation, and wind, from cooperating members with observation networks and maintains an archive of the MRMS-QPE Project for public use (IEM, 2022).

Flood hazard mapping is an essential tool for flood hazard and risk management analysis (Mudashiru *et al.*, 2021). The main tools used to assess inundation areas are hydraulic and hydrologic models, which simulate flood events, identify vulnerable areas, and create flood management plans (Mihu-Pintilie *et al.*, 2019).

The United States Army Corps of Engineers (USACE) model River Analysis System (HEC-RAS) is an essential tool for hydrologic modeling, hydraulic design, and water management (Halwatura and Najim, 2013) and can be used for simulating major storm events and flood maps (Garcia and Bedient, 2020; Pistocchi and Mazzoli, 2002; Beavers, 1994). Researchers have applied one dimension HEC-RAS (1D) in various case studies, such as the Fenton River in Connecticut (Stella, 2022), the Copper Slough Watershed in Illinois (Thakur *et al.*, 2017), and the San Antonio River Watershed in Texas (Knebl *et al.*, 2005). Knebl *et al.* (2005) demonstrated that HEC-RAS 1D is a very effective tool for hydrological forecasts of flooding on a regional scale when coupled with the Next Generation Weather Radar (NEXRAD) rainfall.

According to Vozinaki *et al.* (2017), the combination of one and two dimension HEC-RAS (1D/2D) modeling is more effective than the HEC-RAS 1D model when high-resolution topographic data is available. This approach allows channel flows to be represented in 1D and overbank flows to be modeled in 2D (Dasallas *et al.*, 2019). Brunner and Gibson (2005) also found HEC-RAS 2D to be a flexible model capable of handling complex hydraulic systems with subcritical, supercritical, and mixed flow regimes. Additionally, the use of property tables enables a more precise representation of terrain to achieve accurate results. Dasallas *et al.* (2019) found that the HEC-RAS 2D model consistently outperformed both the HEC-RAS 1D and HEC-RAS 1D/2D models. Ghimire *et al.* (2022) found that the HEC-RAS 1D model did not provide as detailed 2D information for floodplain areas as the HEC-RAS 1D/2D model did. On the other hand, the disadvantage of using the 2D model is that it requires substantial computational time and a high resolution grid (Vozinaki *et al.*, 2017).

This study proposes an alternative modeling approach to HEC-RAS 1D and 1D/2D by utilizing a full HEC-RAS 2D grid model forced by MRMS-QPE grid precipitation during the occurrence of Alex Hurricane during June-July 2010 in the State of Nuevo Leon, Northeast Mexico. The Santa Catarina River Watershed was selected as the study area for model development. The watershed has a hydrometric station located in the town of Cadereyta near the city of Monterrey. The HEC-RAS 2D grid model was utilized to simulate flood and velocity maps of the Santa Catarina River watershed, the simulated stages of the model were calibrated against observed values at Cadereyta Hydrometric Station applying the evaluation coefficients R-squared and Nash - Sutcliffe model of efficiency.

2. MATERIALS AND METHODS

2.1. Characteristics of the watersheds

The study area for this research (Figure 1) is the Santa Catarina River watershed, which is part of the Bravo-Conchos Watershed located in the state of Nuevo Leon, Northeastern Mexico bordering the USA and includes part of the MMA, capital of the state of Nuevo Leon.

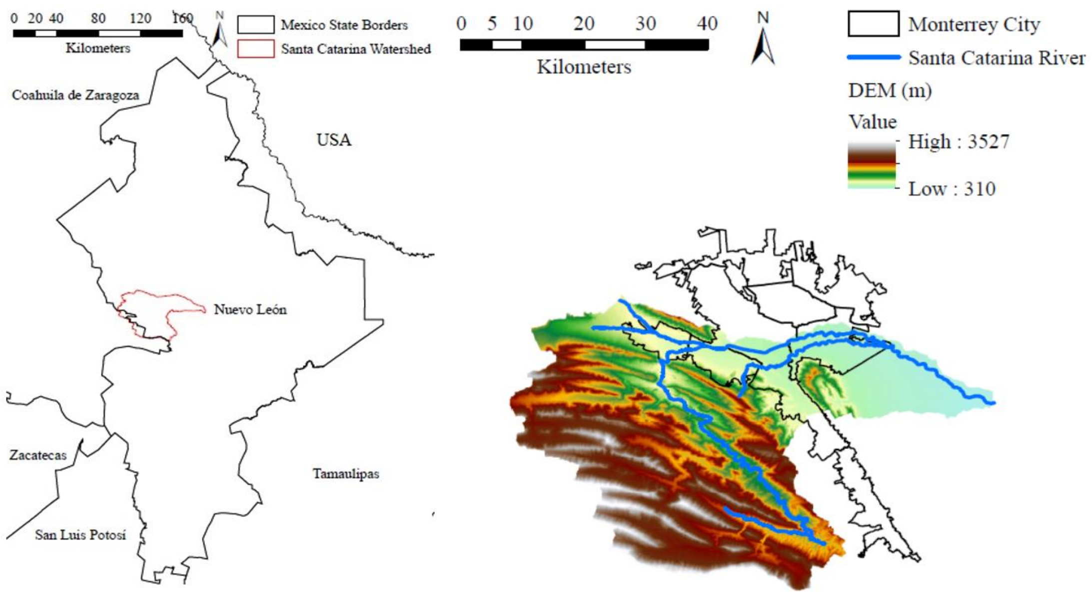

Figure 1. State of Nuevo Leon, Santa Catarina Watershed and Monterrey City.

The watershed has a drainage area of 1831 km^2 and a relief of 3260 m (Cázares-Rodríguez *et al.*, 2017). The Santa Catarina River Watershed has a subtropical semi-arid climate, with hot summers and occasional frosts in some winters (Návar and Synnott, 2000). According to the climatic classification of Köppen the MMA is in a semi-arid zone (BSh). The mean annual temperature is 21.5°C with a mean annual precipitation of 602 mm, with most of the rainfall occurring in between the months of August and September (Aguilar-Barajas *et al.*, 2019). The MMA has a population of approximately 4 million people spread mainly horizontally reaching

an area of almost 900 km^2 in 2010 (Aguilar-Barajas *et al.*, 2019).
Land Cover is dominated by Shrublands, secondary shrublands and mixed woodlands, Table 1 summarize Land Cover class and Soil class by percent of coverage (Cázares-Rodríguez *et al.*, 2017).

Table 1. Land cover and Soil by % of coverage.

Land Cover class	Coverage (%)	Soil class	Coverage (%)
Shrublands	32.92	Lithosol	94.23%
Secondary shrublands	23.09	Regosol	1.07%
Mixed woodlands	20.83	Rendzina	0.76%
Human settlements	6.57	Xerosol	0.51%
Agriculture	3.88	Phaeozem	0.48%
Grasslands	2.07	Castañozem	0.44%

The Santa Catarina River is born in the upper part of the canyons of La Huasteca in the Sierra Madre Oriental, downstream across the MMA with the Caldereyta Hydrometric Station as the outlet of the watershed (Aguilar-Barajas *et al.*, 2019).

The Rompepicos Dam, located at the Corral de las Palmas upstream of the MMA, was completed by 2004 after planning stages in 1997 (Cázares-Rodríguez *et al.*, 2017). The project was authorized to provide flood protection for the MMA (Schrader and Balli, 2018). The Rompepicos Dam has a gravity curtain with an elevation of 70 m and a maximum length of 240 m, with two outlets, a rectangular culvert of 6x6 m at the base of the dam with a capacity of 838 m^3/s, and a Creager spillway with a crest of 60 m and a capacity of 3376 m^3/s at the maximum design elevation (Cázares-Rodríguez *et al.*, 2017).

2.2. HEC-RAS and MRMS-QPE precipitation datasets

Data for the application of HEC-RAS 2D models such as Digital Elevation Model (DEM) with 1x1 m resolution and 0.10 m RMSE was obtained from the United States Geological Service (USGS, 2022). Land Cover and Soil layers from the Instituto Nacional de Estadísticas y Geografía (INEGI, 2015). Discharges and Stages with 1 hour time step and some missing values of stages were obtained from the Comision Nacional del Agua (CONAGUA, 2015) at Cadereyta Hydrometric Station # 24327. MRMS-QPE grid precipitation with 5 minutes time step and 4000 m resolution was obtained from the IEM (2022) (Table 2).

Table 2. Data sources for DEM, land cover, soil type discharges, stages, and precipitation.

Data	Data source
DEM	(USGS, 2022)
Land cover	(INEGI, 2015)
Soil class	(INEGI, 2015)
Precipitation	(IEM, 2022)
Stages	(CONAGUA, 2015)

2.3. Evaluation coefficient

During Alex Hurricane, the streamflow gauges that were available in the Santa Catarina River watershed were either destroyed or not functioning properly (Cázares-Rodríguez, 2017), thus limiting the available options for model calibration. During the event, only two hydrologic observations were available. The continuous stages recorded at Cadereyta Hydrometric Station by CONAGUA (2015) and a visually estimated maximum water level at Rompepicos Dam, 2.5

m below the spillway (Cázares-Rodríguez, 2017). The observed stages of the Santa Catarina River at Cadereyta Hydrometric Station were used to conduct the calibration of the HEC-RAS 2D model applying the evaluation coefficients R-squared (r^2) and Nash - Sutcliffe (NS) model of efficiency.

R-squared regression coefficient of determination (r^2) is the most-used statistical process to assess the degree of fit of a model; the value measures how much variation the trend line has, given by Equation 1 (Akossou and Palm, 2013).

$$r^2 = \frac{SCE_P}{SCE_{tot}} \quad (1)$$

Where:

SCE_p: means the sum of squares related to regression

SCE_{tot}: the total sum of squares

The nearer r^2 is to 1, the better the trend line fits the data (Akossou and Palm, 2013).

Nash - Sutcliffe (NS) model of efficiency (Nash and Sutcliffe, 1970), given by Equation 2.

$$NS = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (2)$$

Where:

O_i: Observed discharges

$\bar{O}$: Mean of observed discharges

S_i: Simulated discharges

n: Number of steps modeled

The closer the simulated NS is to 1, the more accurate the model is. If NS < 0, it means that the observed data mean is a better predictor than the simulated values (Stella, 2021).

3. RESULTS AND DISCUSSION

A HEC-RAS 2D model was designed for the Santa Catarina River watershed using a 500x500 m grid in the whole watershed, a 50x50 m grid along the mainstream of the Santa Catrina River, a NAD27 Projection and 1 minute running time step. The spacing of the whole grid (500x500 m) was chosen to represent floods in the rural upstream watershed and a grid of 50x50 m for a better representation of floods along the whole mainstream of the Santa Catarina River was introduced as break lines.

Land Cover and Soils Layers were used as input to obtain Curve Number (CN), Manning Number (N_m), Abstraction Ratio, Infiltration Rate and Percent of Impervious Land (% Imp.) parameters, in the Santa Catarina River watershed.

Classification polygons were created in the Land Cover and Soils layers along the mainstream of the Santa Catarina River with N_m and % Imp. as parameters to calibrate the model against the observed stages at Cadereyta Hydrometric Station. The Santa Catarina River watershed outlet is located at Cadereyta Hydrometric Station represented with a Normal Depth = 0.0021 as Boundary condition. Initial conditions for the simulation were included as interpolated results from a previous run, the chosen file was the final date/time of the plan, July

5th, 2010 at 23:00 PM.

A dam, a culvert and a spillway in the Rompepicos Dam and 39 Bridges are included in the model. These hydraulic structures were located using Google Maps (Google Earth, 2022), but buildings were not represented. Figure 2 shows HEC-RAS 2D model schematic of the Santa Catarina River Watershed. Parameter layers CN, Mn, Abstraction Ratio, Infiltration Rate and % Imp. in the 50x50 meter grid are represented as Border Conditions in the Figure 2.

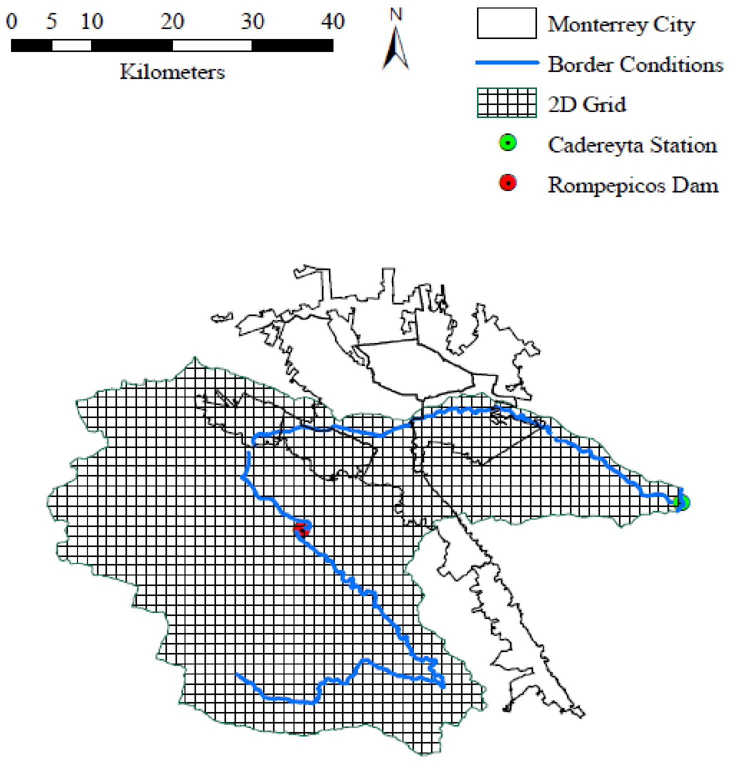

Figure 2. Schematic of the HEC-RAS 2D model.

The simulated stages of the model were calibrated against observed values at Cadereyta Hydrometric Station from June 30th, 2010 at 22:00 PM to July 5th, 2010 at 23:00 PM. Manning's number and Percent of Impervious Land obtained after the calibration were N_m = 0.02, corresponding to pit and gravel and % Imp = 100%. Figure 3 shows the observed and simulated stages after calibration of the HEC-RAS 2D model.

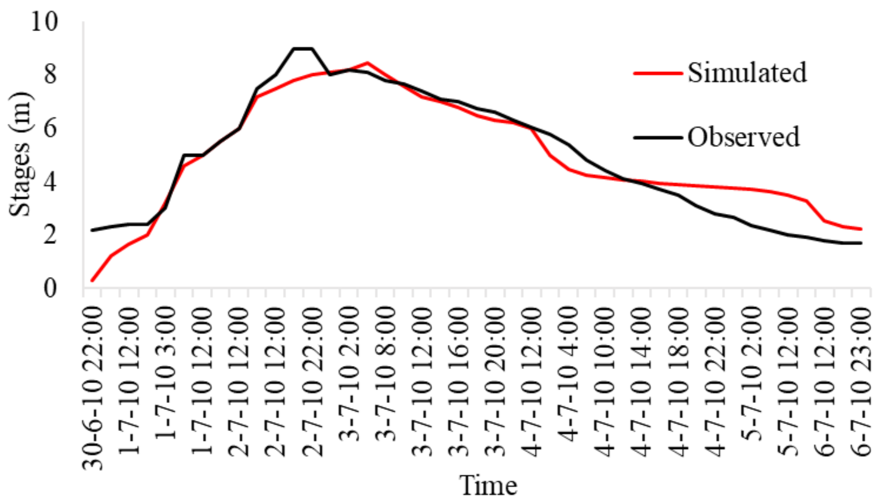

Figure 3. Observed and simulated stages at Cadereyta Hydrometric Station.

The calibrated values of the observed peak stages were 9.0 m against the simulated of 8.5 m and the observed time to peak was July 2nd at 20:00 PAM against the simulated July 3rd at 04:00 Am. Table 3 shows observed and simulated peak and time to peak stages obtained after calibration at Cadereyta Hydrometric Station.

Table 3. Peak and time to peak stage.

Parameter	Observed	Simulated
Peak stage (m)	9.0	8.5
Time to peak	July 2nd 20:00 PM	July 3rd at 04:00 AM

The calibrated values of the observed against the simulated stages have an $r^2 = 0.90$ and NS = 0.98. Table 4 summarizes the R-squared and Nash - Sutcliffe coefficients obtained after calibration at Cadereyta Hydrometric Station.

Table 4. R-squared (r^2) and Nash - Sutcliffe (NS) coefficients.

Coefficients	Stages
r^2	0.90
NS	0.98

Also, the visually estimated maximum water level behind Rompepicos Dam of 2.5 m was used as reference to compare with the simulated maximum water level of 2.8 m below the crest.

Figure 4 shows the simulated Flood map of the Santa Catarina River corresponding to the maximum inundation area obtained during July 2nd at 02:00 PM.

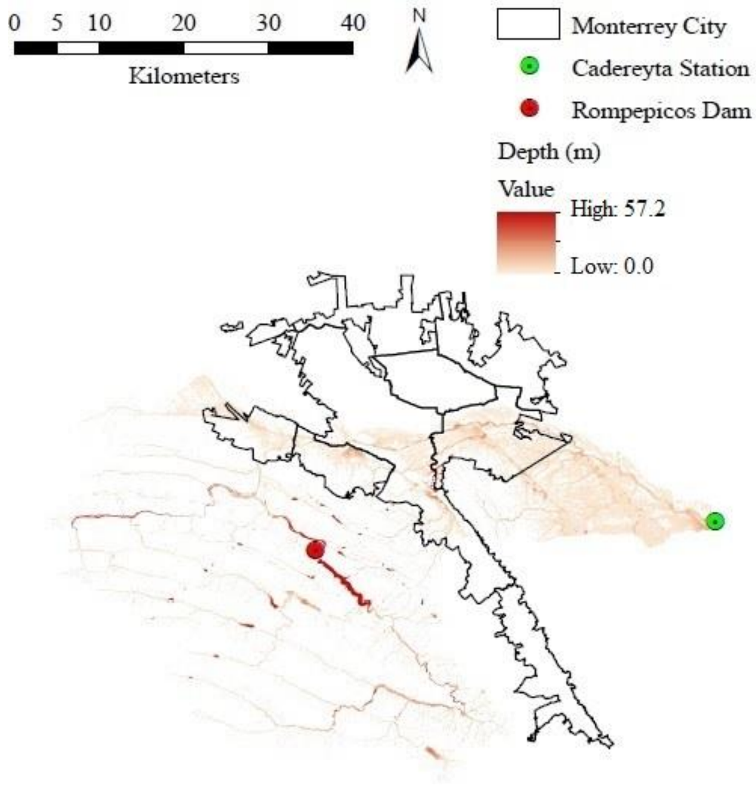

Figure 4. Flood map simulated.

Figure 5 shows the simulated Velocity map of the Santa Catarina River watershed corresponding to the maximum inundation area obtained during July 2nd at 02:00 AM.

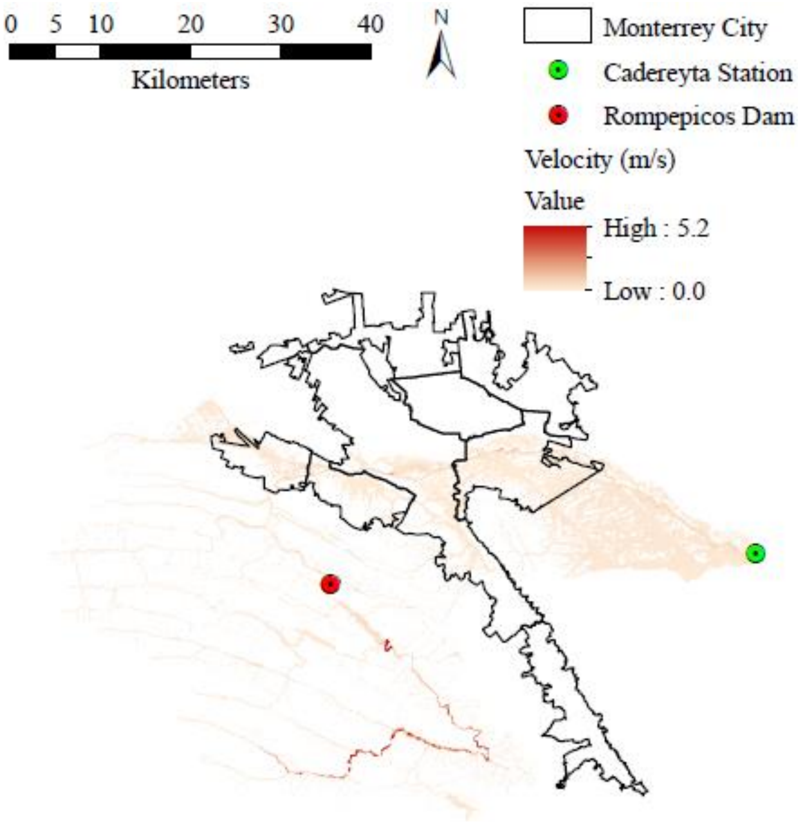

Figure 5. Velocity map simulated.

Table 5, summarizes the simulated maximum flood area, stream water depth and stream water velocity obtained during July 2nd at 02:00 AM.

Table 5. Maximum simulated flood area, water depth, velocity, peak flow, and stage.

Parameter	Value
Maximum flood area (Km^2)	289.3
Maximum water depth (m)	57.2
Maximum water velocity (m/s)	5.2

Alex Hurricane was a single and unique event and due to its extreme nature; available streamflow gauges were either destroyed or not operating during the hurricane, thus limiting the available options for model calibration and validation. During the event, the only hydrologic observations available were at Rompepicos Dam and the Cadereyta Hydrometric Station.

The resulting simulation achieved a simulated peak stage of 8.5 against an observed of 9.0 m, a r^2 of 0.90 and a NS coefficient of 0.98 at Cadereyta Hydrometric Station, showing that the HEC-RAS 2D model has a high degree of accuracy after calibration. Due to the lack of data for validation, the visually estimated maximum water level below the crest of 2.5 m at Rompepicos Dam can be used as a confirmation point to compare with the maximum water level simulated of 2.8 m.

The very high depths in the flood map are from 2 sources: a) The Rompepicos Dam Reservoir with a 60 m spillway crest, was accumulating water during the event and, b) The La

Huasteca very narrow canyons, upstream of the Santa Catarina River in the mountain zone, creating high depths during the flood event.

The peak to time difference between observed and simulated stages at Cadereyta Hydrometric Station was 8 hours, the temporal lag can be attributed to the uncertainties that precipitation data had within. MRMS-QPE grid precipitation interpolation was designed for USA users, with sensors taking data and interpolating inside USA borders. Due to the fact that the MMA is near the USA border, the watershed is covered by MRMS-QPE grid precipitation data, but probably the interpolated data obtained in the borders have a poor lag time quality compared with the whole USA coverage. Besides the differences in current time between the MMA and the source of MRMS-QPE grid precipitation data at the city of Ames in the State of Iowa, USA.

4. CONCLUSIONS

The primary objective of this study was to assess the performance of a HEC-RAS 2D model, driven by MRMS-QPE grid precipitation, in simulating flood and velocity patterns during an extreme flood event known as Alex Hurricane in the Santa Catarina River Watershed, located in the State of Nuevo Leon, Mexico. The methodology and development of the flood and velocity map model are presented in this manuscript. For the simulation of the Alex Hurricane event, MRMS-QPE grid precipitation data was used as input to drive the HEC-RAS 2D model and simulate water levels, flood extents, and velocity maps within the Santa Catarina River Watershed. The simulated water levels were calibrated by comparing them with observed values at the Cadereyta Hydrometric Station. Additionally, the visually estimated maximum water level below the crest at Rompepicos Dam served as a confirmation point. The calibration of the model involved adjusting Manning's number and the Percent of Impervious land parameters.

The process to design the HEC-RAS 2D model coupled with MRMS-QPE grid precipitation is user friendly to set-up, shows stability and the capacity to simulate flood and velocity maps along the whole Santa Catarina River Watershed with accuracy.

One of the significant challenges faced by hydrologic and hydraulic models when simulating discharges and stages is the requirement for high-quality spatial data. The utilization of precise data such as DEM and MRMS-QPE grid precipitation with high resolution is crucial in achieving a high level of accuracy during the simulation process. However, the lack of precise stage measurements during the event hinders the ability to achieve optimal results with the HEC-RAS 2D model.

It should be noted that both DEM and MRMS-QPE data sources are from the United States, but were used outside of U.S. borders due to their spatial coverage including the Santa Catarina Watershed. Consequently, the temporal delay between observed and simulated peak stages can be attributed to the uncertainties inherent in the precipitation and elevation data. An improvement in hydrologic modeling accuracy can be achieved by obtaining such data from sources within the countries where the events occur.

The effective integration of MRMS-QPE grid precipitation into the HEC-RAS 2D model demonstrates the potential for generalizing this methodology to other intricate watersheds, thereby maximizing the strengths of the 2-dimensional model. In future studies, various scenarios can be simulated using this approach, including flood diversion, the construction of new dams along the Santa Catarina River, and dam break and overtopping analyses of the Rompepicos Dam. These simulations have the potential to provide valuable insights to stakeholders and decision-makers in the Metropolitan Area. Such information can aid in making informed decisions and developing strategies related to flood management and infrastructure development within the watershed.

5. ACKNOWLEDGEMENTS

The author acknowledges the assistance and thanks the anonymous reviewers of the Revista Ambiente & Água for their contributions, which enriched this document.

6. REFERENCES

AGUILAR-BARAJAS, I.; SISTO, N. P.; RAMIREZ, A. I.; MAGAÑA-RUEDA, V. Building urban resilience and knowledge co-production in the face of weather hazards: flash floods in the Monterrey Metropolitan Area (Mexico). **Environmental Science & Policy**, 99, pp. 37-47, 2019. https://doi.org/10.1016/j.envsci.2019.05.021

AKOSSOU, A. Y. J.; PALM, R. Impact of data structure on the estimators R-square and adjusted R-square in linear regression. **Journal of Computational Mathematics**, v. 20, n. 3, p. 84-93, 2013.

BEAVERS, M. A. **Floodplain Determination Using HEC-2 and Geographic Information Systems**. Master's Thesis - The University of Texas, Austin, 1994.

BRUNNER, G. W.; GIBSON, S. Sediment transport modeling in HEC RAS. *In*: LETCHER, T. (ed.). **Impacts of global climate change**. Elsevier, 2005. p. 1-12.

CÁZARES-RODRÍGUEZ, J. E.; VIVONI, E. R.; MASCARO, G. Comparison of two watershed models for addressing stakeholder flood mitigation strategies: Case study of Alex Hurricane in Monterrey, Mexico. **Journal of Hydrologic Engineering**, v. 22, n. 9, p. 05017018, 2017. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001560

COMISIÓN NACIONAL DEL AGUA (Mexico); BANCO NACIONAL DE DATOS DE AGUAS SUPERFICIALES. **Sistema de Información Hidrológica (SIH)**. México, DF, 2015. Available at: ftp://hidros:hidros@sih.conagua.gob.mx/ Access: 12 October, 2022.

DASALLAS, L.; KIM, Y; AN, H. Case study of HEC-RAS 1D–2D coupling simulation: 2002 Baeksan flood event in Korea. **Water**, v. 11, n. 10, p. 2048, 2019. https://doi.org/10.3390/w11102048

DROEGEMEIER, K. K.; KELLEHER, K.; CRUM, T. D.; LEVIT, J. J.; GRECO, S. A. D.; MILLER, L. *et al.* Project CRAFT: A test bed for demonstrating the real time acquisition and archival of WSR-88D base (Level II) data. *In*: INTERNATIONAL CONFERENCE ON IIPS METEOROLOGY, OCEAN AND HYDROLOGY, 18., 2002, Orlando. **Posters[…]** Orlando, FL: AMS, 2002.

FERRIÑO-FIERRO, A.; GUERRA-COBIÁN, V.; BRUSTER-FLORES, J.; DE LIRA-REYES, G.; CAVAZOS-GONZALEZ, R. Control de inundaciones en zonas urbanas, caso de estudio: Presa Rompe Picos Corral de Palmas ubicada en Santa Catarina, Nuevo León, México. **Ciencia FIC,** v. 1, p. 5-9, 2010.

FUENTES-MARILES, O. A.; FRANCO, V.; LUNA-CRUZ, F.; VÉLEZ-MORALES, L.; MORALES-RODRÍGUEZ, H. L. **Caracterización fluvial e hidráulica de las inundaciones en México convenio CNA-SGTGASIR-09/2014, organismo de cuenca X, Golfo centro ciudad de Veracruz, Veracruz ríos Jamapa y Cotaxtla**. México, DF, Comisión Nacional del Agua; Instituto de Ingeniería, UNAM, 2014.

GARCIA, M. J. A.; BEDIENT, P. Integrating Reservoir Operations and Flood Modelling with HEC-RAS 2D. **Water**, v. 12, n. 8, p. 2259, 2020. https://doi.org/10.3390/w12082259

GOOGLE EARTH. **Beaumont, USA**. Available at: http://www.earth.google.com. Access: 12 October, 2022.

GHIMIRE E.; SHARMA S.; LAMICHHANE N. Evaluation of one-dimensional and two-dimensional HEC-RAS models to predict flood travel time and inundation area for flood warning system. **ISH Journal of Hydraulic Engineering,** v. 28, n. 1, p. 110-126, 2022. https://doi.org/10.1080/09715010.2020.1824621

GONZÁLEZ-ALEMÁN, J. J.; EVANS, J. L.; KOWALESKI, A. M. Use of ensemble forecasts to investigate synoptic influences on the structural evolution and predictability of Alex Hurricane in the midlatitudes. **Monthly Weather Review**, v. 146, n. 10, p. 3143-3162, 2018, 2016. https://doi.org/10.1175/MWR-D-18-0015.1

HALWATURA, D.; NAJIM, M. M. M. Application of the HEC-HMS model for runoff simulation in a tropical catchment. **Environmental modeling & software**, v. 46, p. 155-162, 2013. https://doi.org/10.1016/j.envsoft.2013.03.006

INEGI. **Website**. 2015. Available in: https://www.inegi.org.mx/ Access: 12 October, 2022.

IEM. **Iowa State University of Science and Technology**. 2022. Available at: https://mesonet.agron.iastate.edu/disclaimer.php Access: 12 October, 2022.

KELLEHER, K. E.; DROEGEMEIER, K. K.; LEVIT, J. J.; SINCLAIR, C.; JAHN, D. E.; HILL, S. D. *et al.* Project craft: A real-time delivery system for nexrad level ii data via the internet. **Bulletin of the American Meteorological Society,** v. 88, n. 7, p. 1045-1058, 2007. https://doi.org/10.1175/BAMS-88-7-1045

KITZMILLER, D.; MILLER, D.; FULTON, R.; DING, F. Radar and multisensor precipitation estimation techniques in National Weather Service hydrologic operations. **Journal of Hydrologic Engineering**, v. 18, n. 2, p.133-142, 2013. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000523

KNEBL, M. R.; YANG, Z. L.; HUTCHISON, K.; MAIDMENT, D. R. Regional scale flood modeling using NEXRAD rainfall, GIS, and HEC-HMS/RAS: a case study for the San Antonio River Watershed Summer 2002 storm event. **Journal of Environmental Management**, v. 75, n. 4, p. 325-336, 2005. https://doi.org/10.1016/j.jenvman.2004.11.024

MIHU-PINTILIE, A.; CÎMPIANU, C. I.; STOLERIU, C. C.; PÉREZ, M. N.; PAVELUC, L. E. Using high-density LiDAR data and 2D streamflow hydraulic modeling to improve urban flood hazard maps: A hec-ras multi-scenario approach. **Water**, v. 11, p. 1832, 2019. https://doi.org/10.3390/w11091832

MUDASHIRU, R. B.; SABTU, N.; ABUSTAN, I.; BALOGUN, W. Flood hazard mapping methods: A review. **Journal of Hydrology**, v. 603, p.126846, 2021. https://doi.org/10.1016/j.jhydrol.2021.126846

NASH, J. E.; SUTCLIFFE, J. V. River flow forecasting through conceptual models: Part 1 – a discussion of principles. **Journal of Hydrology**, v. 10, n. 3, p. 282–290, 1970. https://doi.org/10.1016/0022-1694(70)90255-6

NOAA. **Multi-Radar/Multi-Sensor System (MRMS)**. 2022. Available in: https://www.nssl.noaa.gov/projects/mrms/ Access: 12 October, 2022.

NÁVAR, J.; SYNNOTT, T. J. Surface runoff, soil erosion, and land use in Northeastern Mexico. **Terra Latinoamericana**, v. 18, n. 3, p. 247-253, 2000.

PASCH, R. J. Tropical Cyclone Report Alex Hurricane (AL012010) 25 June–2 July 2010. **iAlert.com**, 2010.

PISTOCCHI, A.; MAZZOLI, P. Use of HEC-RAS and HEC-HMS models with ArcView for hydrologic risk management. *In:* INTERNATIONAL CONGRESS ON ENVIRONMENTAL MODELLING SOFTWARE, 1, , 2002, Lugano, Switzerland. **Proceedings[…]** IEMSS, 2002. p. 138. Available in: https://scholarsarchive.byu.edu/iemssconference/2002/all/138 Access: 12 October, 2022.

RAMÍREZ-SERRATO, N. L.; YEPÉZ-RINCÓN, F. D.; GUERRA-COBIÁN, V. H.; FERRIÑO FIERRO, L. A.; LOZANO-GARCÍA, D. F. Modelación hidráulica histórica 2D a partir de fotografías estereoscópicas antiguas para el río Santa Catarina, Nuevo León, México. SIMPOSIO INTERNACIONAL SELPER, 17., 2016, Puerto Iguazú, Argentina. **Proceedings[…]** 2016. Available at: https://www.researchgate.net/publication/333677051_Modelacion_hidraulica_historica_2D_a_partir_de_fotografias_estereoscopicas_antiguas_para_el_rio_Santa_Catarina_Nuevo_Leon_Mexico. Access: 12 October, 2022.

SÁNCHEZ-RODRÍGUEZ, R.; CAVAZOS, T. Amenazas naturales, sociedad y desastres. *In:* CAVAZOS, T. (ed.). **Conviviendo con la Naturaleza**. Tijuana: CONACYT, INECC, CICESE, REDESCLIM, CENAPRED, 2015. p. 4–49.

SCHRADER, E. K.; BALLI, J. A. Presa Rompepicos–a 109 meters high RCC dam at Corral Des Palmas with final design during construction. *In:* BERGA, L. (ed.). **RCC Dams - Roller Compacted Concrete Dams**. London: Routledge, 2018. p. 193-201.

STELLA, J. M. Applying Weibull distribution and Low Flow Frequency Curves for minimum flow prediction in an ungagged stream in Connecticut, New England. **Global Scientific Research in Environmental Science,** v. 1, n. 4, p. 1-9, 2021. https://doi.org/10.53902/GSRES.2021.01.000520

STELLA, J. M. Mapping Floods of Fenton River, an Ungauged Stream in Connecticut. **Journal of Water Resource and Protection**, v. 14, n. 7, p. 531-541, 2022. https://doi.org/10.4236/jwarp.2022.147028

THAKUR, B.; PARAJULI, R.; KALRA, A.; AHMAD, S.; GUPTA, R. Coupling HEC-RAS and HEC-HMS in precipitation runoff modeling and evaluating floodplain inundation map. **Proceedings** WORLD ENVIRONMENTAL AND WATER RESOURCES CONGRESS, 21–25 May 2017, Sacramento, CA. **Papers.[…]** ASCE, 2017, p. 240–251. https://doi.org/10.1061/9780784480625.022

USGS. **The National Maps Viewer**. 2022. Available in: https://viewer.nationalmap.gov/basic/ Access: 12 October, 2022.

VOZINAKI, A. E. K.; MORIANOU, G. G.; ALEXAKIS, D. D.; TSANIS, I. K. Comparing 1D and combined 1D/2D hydraulic simulations using high-resolution topographic data: A case study of the Koiliaris watershed, Greece. **Hydrological Sciences Journal,** v. 62, n. 4, p. 642-656, 2017. https://doi.org/10.1080/02626667.2016.1255746

ZHANG, J.; QI, Y.; HOWARD, K.; LANGSTON, C.; KANEY, B.; ORTEGA, K.; SMITH, T. *et al.* Retrospective Analysis of High-Resolution Multi-Radar Multi-Sensor QPEs for the United States. AGU FALL MEETING, 2013. **Abstracts[…]** ADS, 2013. p. H41I-1357. Available at https://ui.adsabs.harvard.edu/abs/2013AGUFM.H41I1357Z/abstract Access: 29 November, 2022.