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Articles

Modelling flood map during Alex hurricane: Simulation enforced by multisensory precipitation in the city of Monterrey, Mexico

Modelación de mapa de inundaciones durante el huracán Alex: simulación usando precipitación multisensorial en la ciudad de Monterrey, México

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Abstract

Alex hurricane was one of the most intense tropical cyclones in the North Atlantic that caused fatalities and loses in the Northeast of Mexico due to the flash floods. Flood hazard mapping is a vital tool to assess inundation areas, which can be simulated using hydraulic and hydrologic models. This study describes the modelling of a flood event during Alex hurricane in the Santa Catarina River Watershed, Northeast of Mexico, applying HEC-HMS and two dimensional (2D) HEC-RAS models forced with Multi Radar Multi Sensor-Quantitative Precipitation Estimation (MRMS-QPE). A HEC-HMS model was developed forced by (MRMS-QPE) as input to simulate discharges along the Santa Catarina River. The simulated discharges were introduced as border conditions along the mainstream of the Santa Catarina River inside a HEC-RAS 2D model to simulate a flood map along the mainstream of the Santa Catrina River. The observed against the simulated peak discharges achieved a r^2 of 0.97 and a Nash-Sutcliffe coefficient of 0.97. The observed against the simulated accumulated discharges achieved a r^2 of 0.99 and a Nash-Sutcliffe coefficient of 1.0. The observed against the simulated stages achieved a r^2 of 0.74 and, a Nash-Sutcliffe coefficient of 0.68. The use of HEC-HMS and HEC-RAS 2D models coupled with MRMS-QPE shows that these models are user friendly to setup, the model has stability and the capacity to simulate flood maps along the whole mainstream of the Santa Catarina River with good results.

Keywords: Flood map, HEC-HMS, HEC-RAS 2D, Monterrey MRMS-QPE precipitation, Santa Catarina River.

Resumen

El huracán Alex fue uno de los ciclones tropicales más intensos en el Atlántico norte, causando muertes y pérdidas en el noreste de México debido a las inundaciones. El mapeo de las inundaciones es una herramienta vital para evaluar áreas afectadas, y se puede simular utilizando modelos hidráulicos e hidrológicos. Este estudio describe el modelado de un evento de inundación durante el huracán Alex en la cuenca del río Santa Catarina, noreste de México, aplicando los modelos HEC-HMS y HEC-RAS usando Multi Radar Multi Sensor-Estimación Cuantitativa de Precipitación (MRMS-QPE). Se desarrolló un modelo HEC-HMS utilizando MRMS-QPE como *input* para simular descargas a lo largo del río Santa Catarina. Las descargas simuladas se introdujeron como condiciones de borde a lo largo de la corriente principal del río Santa Catarina dentro de un modelo HEC-RAS bidimensional (2D) para simular un mapa de inundaciones a lo largo de la corriente principal del río Santa Catrina. Las descargas máximas observadas frente a las simuladas por HEC-HMS lograron un r^2 de 0.97 y un coeficiente de Nash-Sutcliffe de 0.97. Las descargas acumuladas observadas contra las simuladas lograron un r^2 de 0.99 y un coeficiente de Nash-Sutcliffe de 1.0. Las alturas observadas contra las simuladas por HEC-RAS lograron un r^2 de 0.74 y un coeficiente de Nash-Sutcliffe de 0.68. El uso de los modelos HEC-HMS y HEC-RAS 2D junto con Multi Radar Multi Sensor-Estimación Cuantitativa de Precipitación muestra que estos modelos son fáciles de configurar; el modelo tiene estabilidad y la capacidad de simular mapas de inundación a lo largo de toda la corriente principal con buenos resultados.

Palabras clave: HEC-HMS, HEC-RAS 2D, mapa de inundaciones, Monterrey, precipitación MRMS-QPE, río Santa Catarina.

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Introduction

Pasch (2010) considered that Alex hurricane was one of the most intense and extremely rare tropical cyclones events since 1938 in the North Atlantic, recorded as Category 2 hurricane (González-Alemán, Evans, & Kowaleski, 2018). Interactions of the tropical moisture with the orographic barriers in the Sierra Madre Oriental led to widespread rainfall in the State of Nuevo Leon, Mexico from June 28 to July 2 (Hernández & Bravo, 2010). Alex hurricane generated an accumulated precipitation of 890 mm recorded at La Estanzuela station in the city of Monterrey, Nuevo León while the estimated average trough the State of Nuevo Leon was over 242 mm (Zarco & Magaña-Lona, 2014) with maximum winds of 205 km/h recorded in one day at La Estanzuela station during June 30 (Fuentes-Mariles, Franco, Luna-Cruz, Vélez-Morales & Morales-Rodríguez, 2014). The flash floods triggered by Alex hurricane caused 22 fatalities in the Monterrey Metropolitan Area (MMA) and an estimated loss of US$2 billion (Sánchez-Rodríguez & Cavazos, 2015).

Flood hazard mapping has undergone significant development during the last century and, are a vital tool in flood hazard and risk management analysis (Mudashiru, Sabtu, Abustan, & Balogun, 2021). The main tools to assess inundation areas are hydraulic and hydrologic models to simulate flood events, search for vulnerable areas and, create a flood management plan (Mihu-Pintilie, Cîmpianu, Stoleriu, Pérez, & Paveluc, 2019).

The Multi Radar Multi Sensor-Quantitative Precipitation Estimation (MRMS-QPE) system is a real time, multisensory precipitation estimates that can provide input to hydrologic models using a grid mesh of 1 km and with a 5-minute time step. This system has been operating since 1997, when the NEXRAD network was deployed (Zhang *et al*., 2013; NOAA, 2022; Kitzmiller, Miller, Fulton, & Ding, 2013). The Iowa Environmental Mesonet (2022) collects precipitation, solar radiation, and wind data from cooperating members with observing networks and maintains an archive of the MRMS-QPE Project for public use (Iowa Environmental Mesonet, 2022).

The United States Army Corps of engineers (USACE) models such as the Hydrologic Engineering Center-Hydrologic Modelling System (HEC-HMS) and River Analysis System (HEC-RAS) have become essential tools for hydrologic modelling, hydraulic design, and water management (Halwatura & Najim, 2013), and can be used for the simulation of major storm events (Garcia, Juan, & Bedient, 2020).

HEC-HMS was designed to simulate the precipitation-runoff processes of dendritic watershed systems (USACE, 2022), the model can be applied for a wide range of geographic areas for solving a broad range of problems, such as: Large river basin water supply, flood hydrology for a small urban or natural watershed (Halwatura & Najim, 2013), with the simulation of surface runoff and peak discharges in the watershed (Chu & Steinman, 2009).

HEC-RAS is a hydraulic model developed by USACE that can create a fully functional modelling environment which allows to cope with virtually all types of problems concerning river networks, including flood maps (Pistocchi & Mazzoli, 2002; Beavers, 1994).

Thakur, Parajuli, Kalra, Ahmad and Gupta (2017) applied HEC-HMS and one-dimensional HEC-RAS (1D) models coupled with gage precipitation in the Copper Slough Watershed, Illinois. Thakur *et al*. (2017) found that forcing the HEC-HMS model with forecasted precipitation can work as flood warning system by generating pre-flood inundation maps with HEC-RAS 1D. Knebl, Yang, Hutchison and Maidment (2005) applied HEC-HMS and HEC-RAS 1D models coupled with Next Generation weather Radar (NEXRAD) rainfall in the San Antonio River watershed, Texas. Knebl *et al*. (2005) research shows that HEC-RAS 1D is a very good tool for hydrological forecasts of flooding on a regional scale. Stella (2022) applied HEC-RAS 1 D model enforce by stream discharges in the Fenton River watershed in October 2005, one of the biggest storms in the watershed to simulate flood maps. Nieto-Butrón, Ramírez-Serrato, Barco-Coyote, Yépez-Rincon and Jacome-Paz (2024) conducted a study to test the impact of vegetation in the Santa Catarina River using IBER hydraulic simulations in the city of Monterrey. Stella (2023) already applied a two-dimensional HEC-RAS model to simulate a flood map using Multisensor grid precipitation in the city of Monterrey. Burgan and Icaga (2019) conducted a flood analysis using Adaptive Hydraulics (ADH) and The Finite Element Surface Water Modeling System (FESWMS) models in the Akarcay watershed in Turkey to simulate flood maps of urban and agriculture lands.

This study focuses on modeling a flood event that occurred during hurricane Alex in mid-2010 in the State of Nuevo Leon, Northeast Mexico. The selected area for model development was the Santa Catarina River Watershed. To generate a flood map of the Santa Catarina River, we first used a HEC-HMS model to simulate discharges in the watershed using MRMS-QPE precipitation data. These simulated discharges were then used as boundary conditions in a two-dimensional HEC-RAS (2D) model to create the final flood map. The next flowchart (Figure 1) will help with the application procedures.

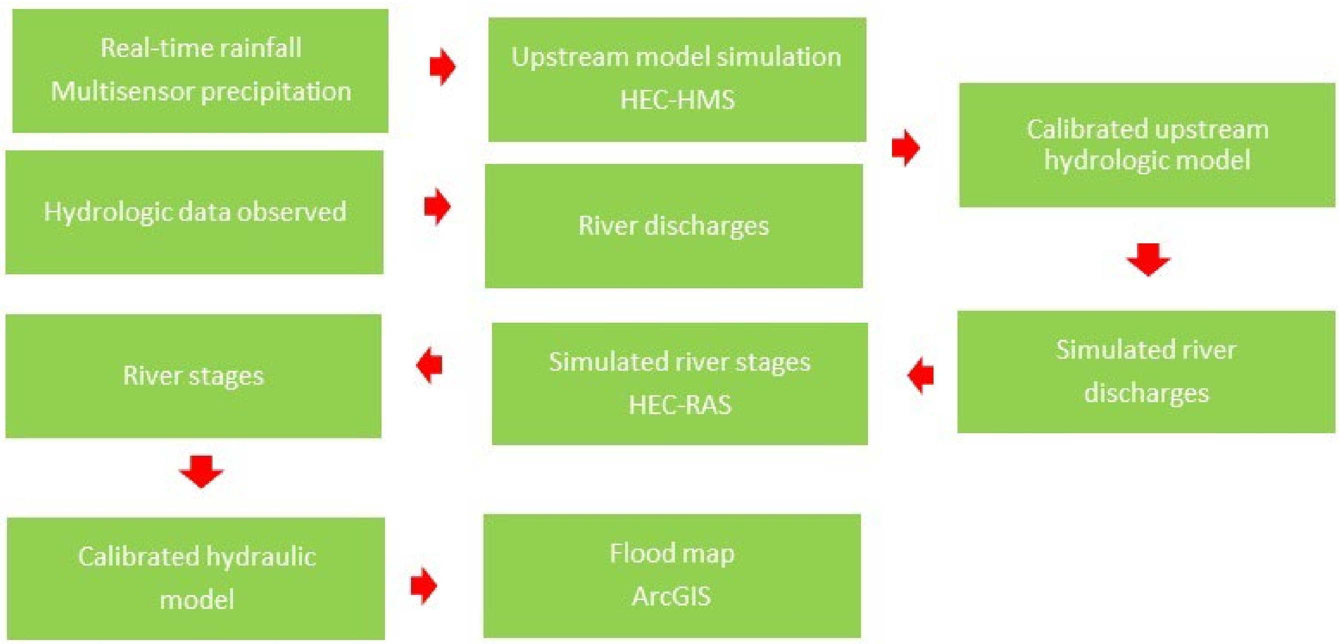

Figure 1. Flowchart of the application procedures.

Materials and methods

Characteristics of the watersheds

The study area for this research is the Santa Catarina River watershed, which is part of the Bravo-Conchos watershed located in the state of Nuevo Leon, Northeastern Mexico and includes part of the MMA, capital of the state and the Santa Catarina River stream (Figure 2).

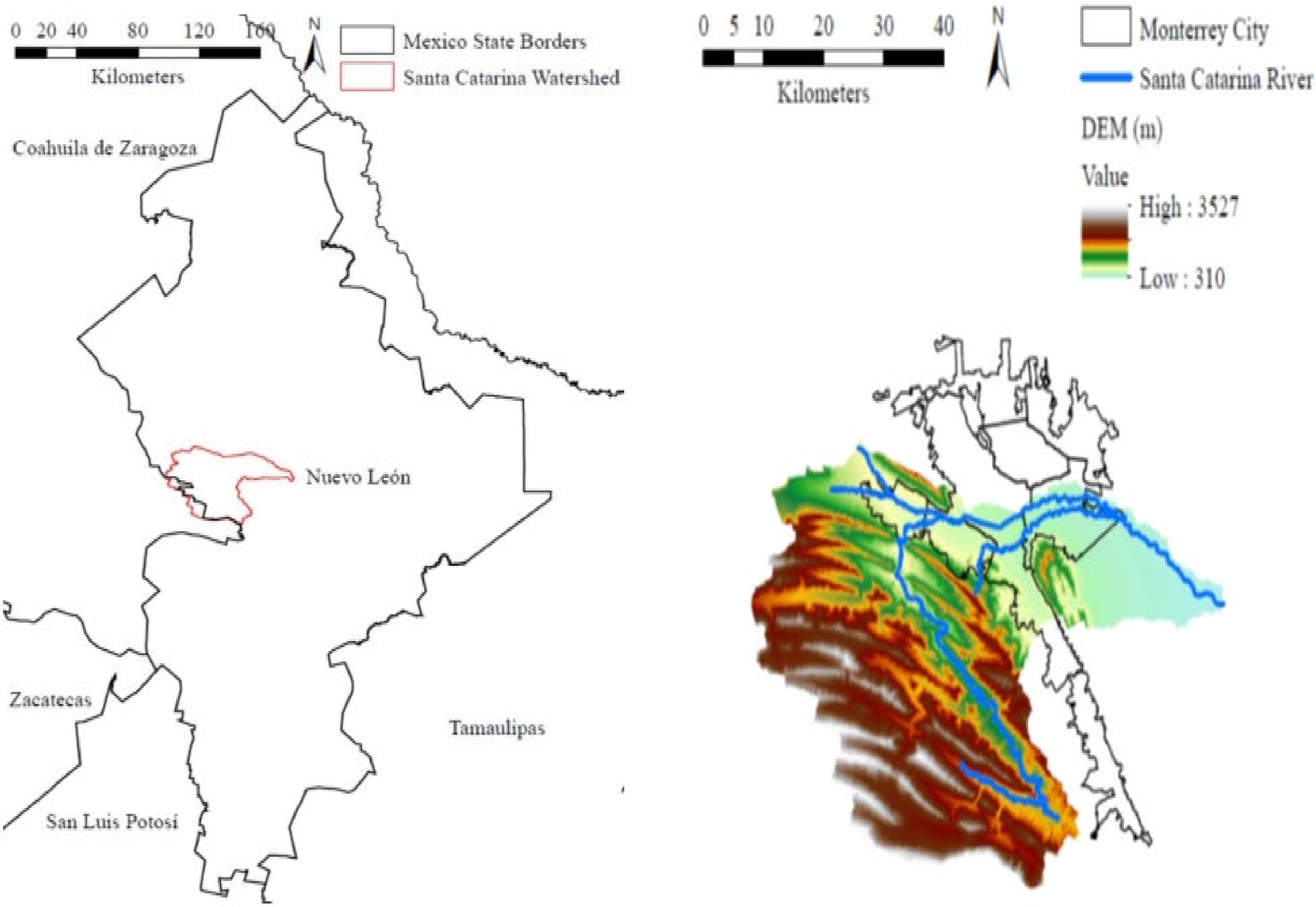

Figure 2. State of Nuevo Leon and the Santa Catarina River Watershed, and MMA.

The watershed has a drainage area of 1 831 km^2 and a relief of 3 260 m (Cázares-Rodríguez, 2016). The Santa Catarina River watershed has a subtropical semi-arid climate, with hot summers and occasional frosts in some winters such as Návar and Synnott (2000) characterized.

According to the climatic classification of Köppen the MMA is in a semi-arid zone (BSh). The mean annual temperature is of 21.5 °C with a mean annual precipitation of 602 mm (SMN, 2010), with most of the rainfall occurring in between the months of August and September (Cázares-Rodríguez, 2016). The MMA has a population of approximately 4 million people spread mainly horizontally (Cázares-Rodríguez, 2016) in 2010 reaching an area of almost 650 km^2.

Land cover is dominated by shrublands, secondary shrublands and mixed woodlands (Cázares-Rodríguez, 2016). Table 1 summarize land cover class by percent of coverage in the Santa Catarina River watershed.

Table 1. Land cover by class.

Land Cover class	Coverage (%)
Shrublands	32.92
Secondary shrublands	23.09
Mixed woodlands	20.83
Human settlements	6.57
Agriculture	3.88
Grasslands	2.07

Soil class is dominated by *lithosols* (Cázares-Rodríguez, 2016), Table 2 summarize soils class by percent of coverage in the Santa Catarina River watershed.

Table 2. Percent of soil class.

Soil class	Coverage (%)
Lithosol	94.23
Regosol	1.07
Rendzina	0.76
Xerosol	0.51
Phaeozem	0.48
Castaňozem	0.44
Vertisol	0.31
Fluvisol	0.06

Monterrey, the capital of the State of Nuevo Leon, Mexico, is situated approximately in the center east of the State located in North East of Mexico, close to the Texas border with a latitude of 25º 45´N and longitude of 100º 15´ W (Aguilar-Barajas, Sisto, & Ramirez, 2015). It has a semi-arid climate by Köppen classification (Aguilar-Barajas *et al*., 2015) with an average yearly temperature of 22.3 ºC, humidity of 79 %, solar radiation of 128 $W.m^{-2}$, and an annual cumulative average value of Precipitation of 590.9 mm (Conagua, 2015).

The climatic phenomena that generate floods in the metropolitan area of Monterrey, occur mainly between June and October, during this period the rains are of great intensity and short duration, which causes flooding such as the hurricanes Gilbert in September of 1988 with 446 mm of precipitation and Alex in July of 2010 with 485 mm (Aguilar-Barajas *et al*., 2015).

The San Juan River watershed vegetative cover around the city of Monterrey is compose mainly by desert-shrug vegetation (62.9 %), agriculture (18.22 %), forest (6.37 %), urban areas (0.53 %) and stratified drift (4.2 %) with a small surface area of barren land (1.4 %) and open water (0.33 %) (INEGI, 2015).

The Santa Catarina River, is born in the upper part of the canyons of La Huasteca in the Sierra Madre Oriental, downstream cross the MMA with the Caldereyta hydrometric station as the outlet of the watershed. Across the Santa Catarina River mainstream there are 39 bridges and culverts from Rompepicos to the outlet of the watershed at Cadereyta Hydrometric Station.

By 2004 a large flood control structure in the mountainous basin upstream of the MMA was completed after planning stages in 1997 after years of consideration (Cázares-Rodríguez, Vivoni, & Mascaro, 2017). The Rompepicos Dam, located at the Corral de Las Palmas, the project was authorized to provide flood protection for the MMA (Schrader & 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 secondary rectangular opening of 6 m x 6 m at the base of the dam with a capacity of 838 m^3/s when the water elevation reaches the maximum design point, and a main Creager spillway with a crest length of 60 m and a capacity of 3 376 m^3/s at the maximum design elevation (Cázares-Rodríguez, 2016).

During the Alex hurricane, only two hydrologic observations were available: A visually estimated maximum water level behind Rompepicos Dam (2.5 m below the spillway) and the continuous discharge record at Cadereyta Hydrometric Station # 24327 by the Comisión Nacional del Agua (Conagua) (Conagua, 2015). However, both observations are

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uncertain given the flood damages occurring along the measured river reach at the Cadereyta Station and the visual inspection of the maximum level in the reservoir rather than a measured water depth (Cázares-Rodríguez *et al*., 2017).

HEC-HMS, HEC-RAS and MRMS-QPE precipitation datasets

Data for the application of HEC-HMS and HEC-RAS 2D models such as Digital Elevation Model (DEM) were obtained from the United States Geological Service (USGS) (USGS, 2022), this is the highest resolution DEM available, and precipitation from the Iowa Environmental Mesonet (2022) is the only multisensory source of precipitation in Mexico for this event. Land cover from the Instituto Nacional de Estadística and Geografía (INEGI) (INEGI, 2015) and, soil type from INEGI (2015) are the data closer to represent the study area during the event. Discharges and, Stages were obtained from Conagua (2015) at Cadereyta hydrometric station # 24327. Table 3 summarize the sources of data.

Table 3. 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	Iowa Environmental Mesonet (2022)
Discharges and stages	Conagua (2015)

Evaluation coefficient

The observed stages of the Santa Catarina River at Cadereyta hydrometric station were used to calibrate and validate the HEC-RAS 2D model. The evaluation was conducted using the r^2 and Nash-Sutcliffe (NS) efficiency coefficients.

(r^2) regression coefficient of determination is the most used statistics to assess the degree of fit of a model, the value measures how much variation the trendline has (Akossou & Palm, 2013), given by Equation (1):

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

Where:

SCE_p = Sum of squares related to regression.

SCE_{tot} = Total sum of squares.

NS model of efficiency (Nash & Sutcliffe, 1970), given by Equation (2):

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

Where:

O_i = Observed discharges.

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Ô = Mean of observed discharges.

S_i = Simulated discharges.

n = Number of steps modeled.

Table 4 summarize coefficient evaluation criteria for r^2 Nash-Sutcliffe (NS) and Root Mean Square Error (RMSE) by Da Silva *et at*. (2015), and Chicco, Warrens and Jurman (2021).

Table 4. Criteria for evaluating the performance of the model.

Model	Value	Performance	Reference
r^2	+1	Best value	Chicco *et al*. (2021)
	- infinite	Worst value	
Nash-Sutcliffe	0.75 < NS < 1.0	Very good	Boskidis, Gikas, Sylaios, and Tsihruntzis (2012)
	0.65 < NS < 0.75	Good	Moriasi *et al*. (2007)
	0.50 < NS < 0.65	Satisfactory	
	0.4 < NS < 0.50	Acceptable	
	NS < 0.4	Unsatisfactory	
RMSE	0.0 < RMSE < 0.50	Very good	Moriasi *et al*. (2007)
	0.50 < RMSE < 0.60	Good	
	0.60 < RMSE < 0.70	Satisfactory	
	RMSE > 0.70	Unsatisfactory	
MAE	0	Best value	Chicco *et al*. (2021)
	+ infinite	Worst value	

Results and discussion

A HEC-HMS model was designed for the Santa Catarina River watershed with a 1-meter DEM resolution and NAD27 projection, the model obtained has 4 subbasins, 4 reaches and 1 sink as outlet. The HEC-HMS project include the following components for the subbasins: A projection, basin and, meteorological models, control specifications, grid and, terrain data, Table 5, summarize the HEC-HMS project processes. The meteorological model includes a time shift of -4 h to match the observed peak discharges, a Reservoir was included in the Rompepicos Dam location and the sink of the model located in Cadereyta hydrometric station.

Table 5. HEC-HMS Project.

Component	Process
Basin model	4 Subbasins, 3 reaches and 1 sink
Meteorological model	Gridded precipitation with a time shift of -4 h
Control specifications	From 06/30/2010 17:00 to 07/05/2010 17:00
Grid data	MRMS-QPE precipitation
Terrain data	DEM 1-meter resolution

Figure 3 shows the schematic of the HEC-HMS model of the Santa Catarina River Watershed; the red line is the sub watershed division.

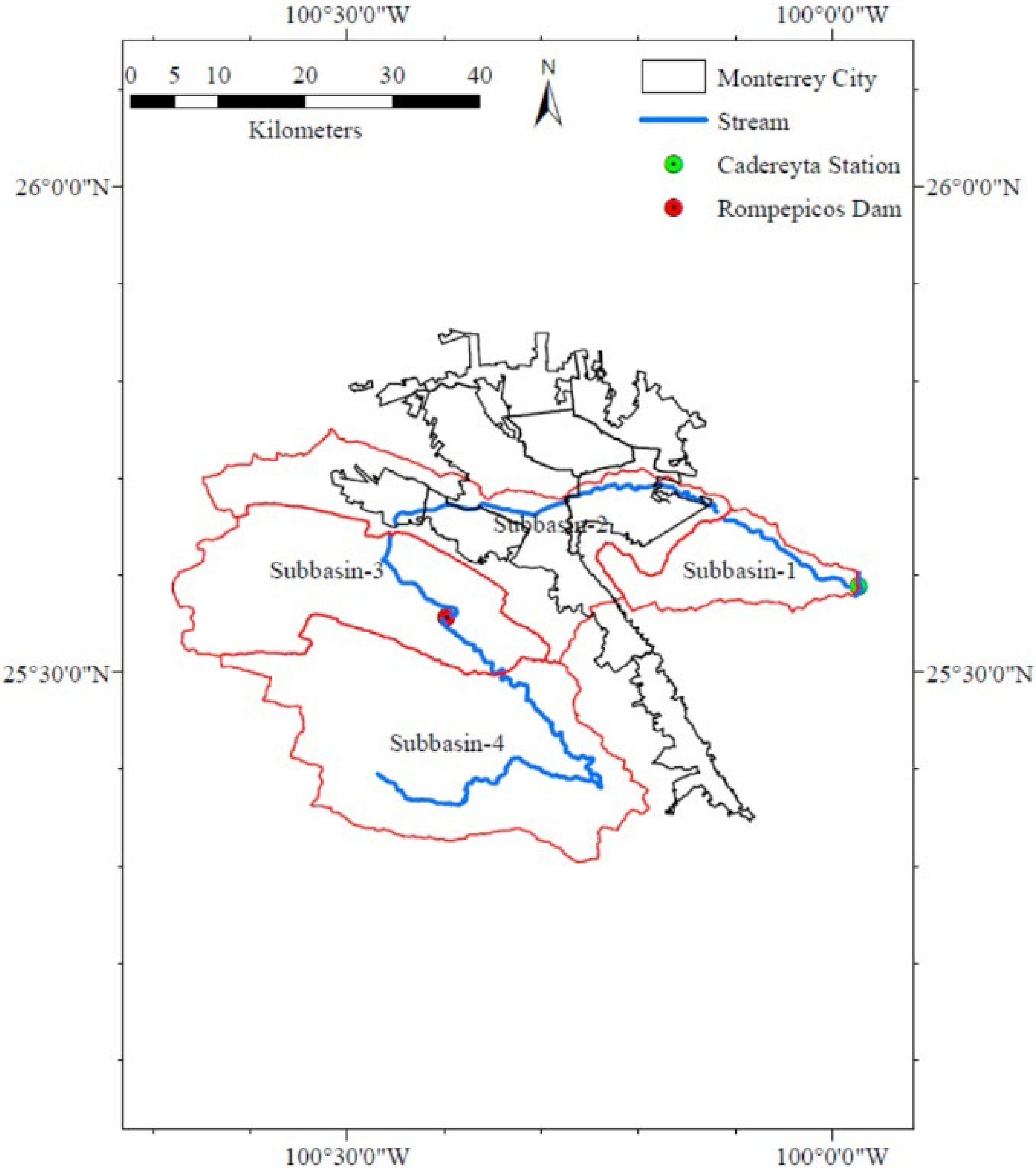

Figure 3. Schematic of the HEC-HMS model.

Subbasin 1 encompasses the city of Monterrey, including the districts of Independencia, Nuevo Repueblo, Caracol, Buenos Aires, Pablo de la Garza, Centro de Guadalupe, Azteca, and the city of Cadereyta.

Subbasin 2 covers the Santa Catarina and San Pedro Garza Garcia districts, as well as Parque La Huasteca.

Subbasin 3 includes locations such as Presa Rompepicos, El Jonuco, Sierra Santa Catarina, and Parque Nacional Cumbres de Monterrey.

Subbasin 4 comprises the areas of Pico Tinajas, El Salto (Cascada), Mirador Don Elio, and La Mano de Dios.

The functions selected to run subbasins processes were, loss with SCS Curve number, transform with SCS Unit Hydrograph, base flow with recession and routing with Muskingum. The HEC-HMS project include the following components for the reaches: routing with Muskingum.

The simulated discharges of the HEC-HMS model were calibrated from 06/30/2010 17:00 PM to 07/05/2010 17:00 PM with the observed discharges at the Cadereyta hydrometric station, the optimized values of the simulated discharges against the observed using CN values as calibration parameter have a r^2 of 0.97 and NS of 0.97. Figure 4 shows the observed and simulated discharges after the calibration of the HEC-HMS model.

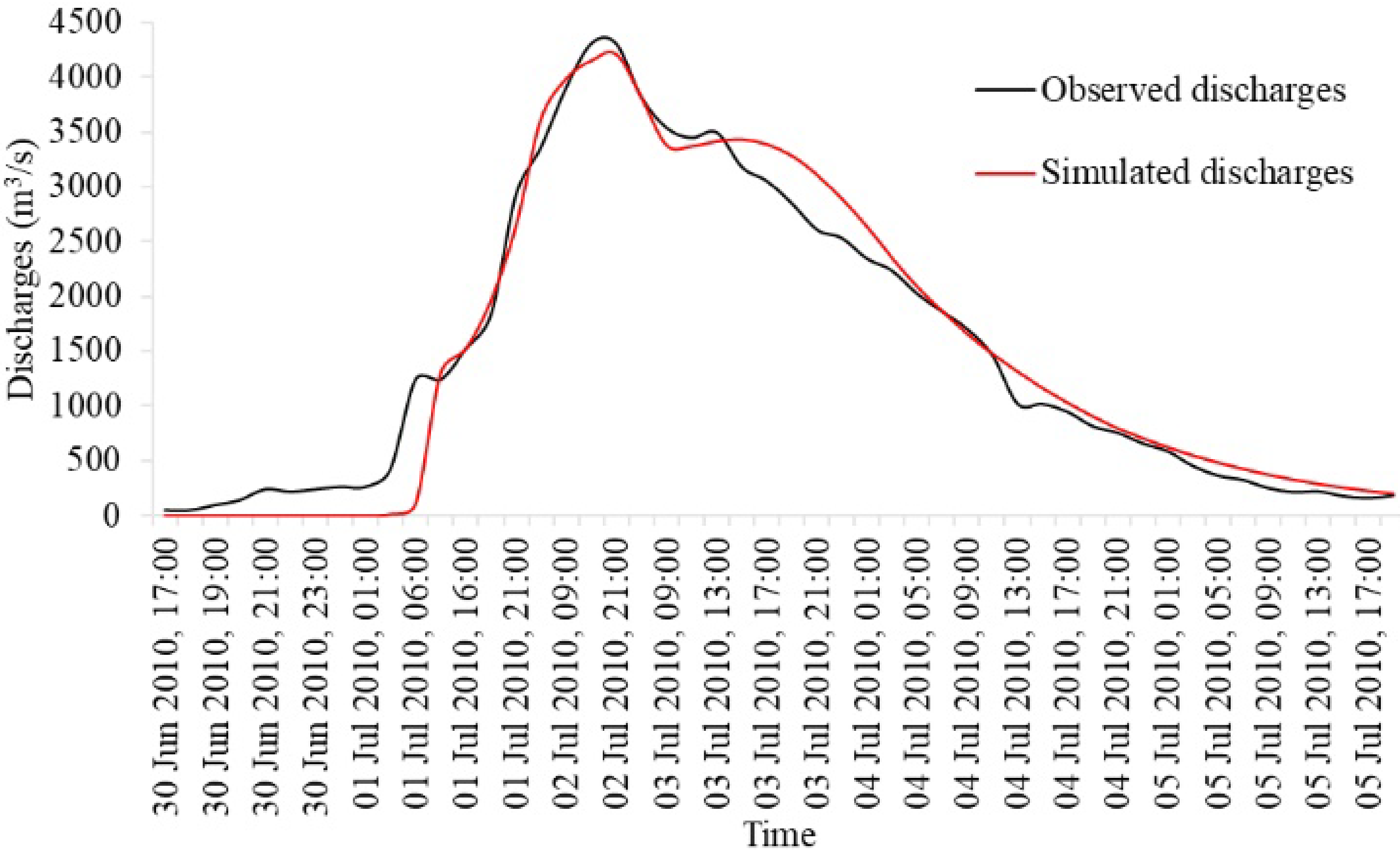

Figure 4. Observed and simulated discharges at Cadereyta hydrometric station.

The accumulated simulated discharges from 06/30/2010 17:00 PM to 07/05/2010 17:00 PM of the HEC-HMS model were compared with the observed accumulated discharges at the Cadereyta hydrometric station, the values have a r^2 of 0.99 and NS of 1.0. Figure 5 shows the observed and simulated accumulated discharges after the calibration of the HEC-HMS model.

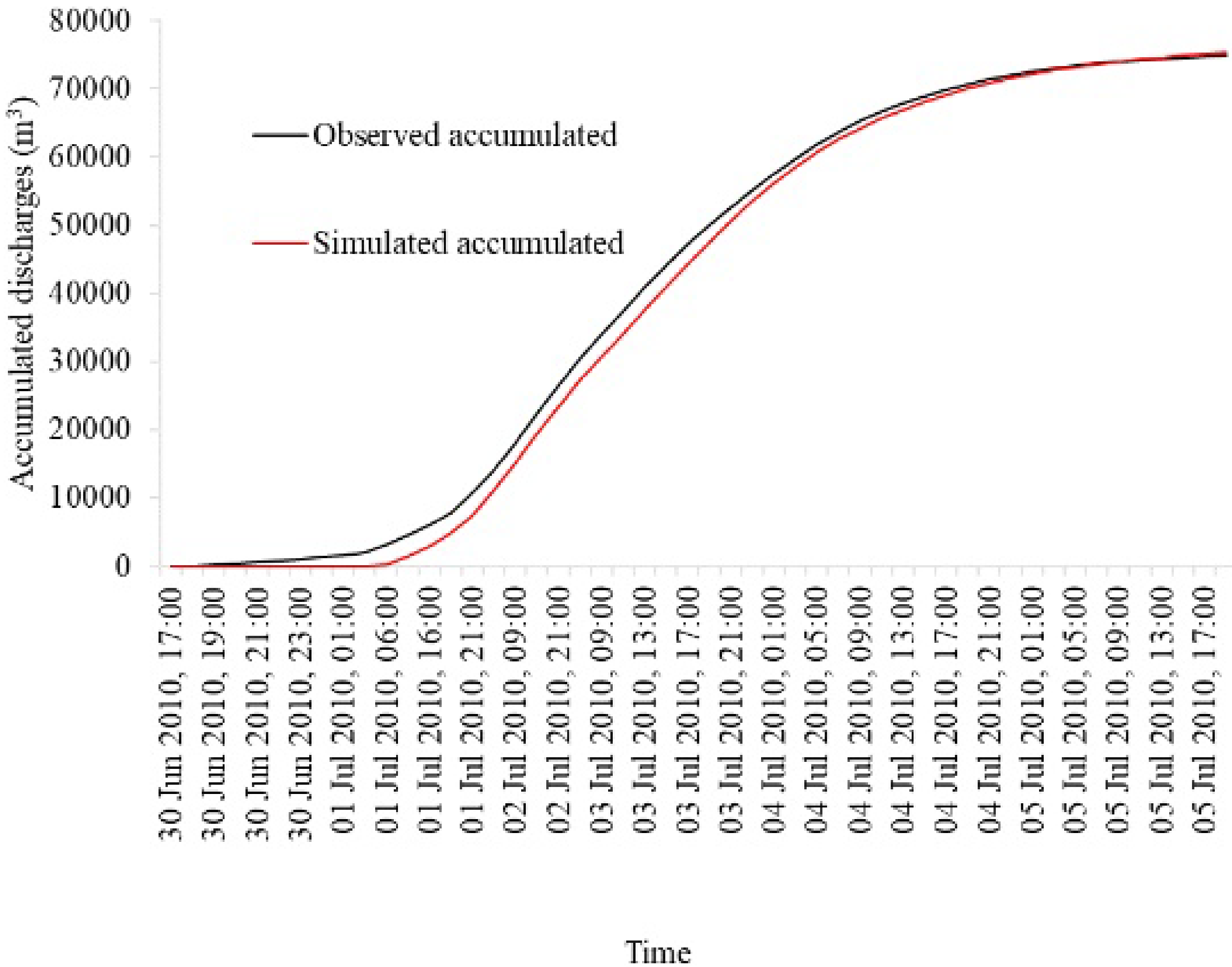

Figure 5. Observed and simulated accumulated discharges at Cadereyta hydrometric station.

A HEC-RAS 2D model was developed for the Santa Catarina River watershed with a 1-meter resolution DEM, with 0.10 meters RMSE, a 500x500 meters Grid and, a NAD27Projection. The spacing of the grid was chosen to preclude any error in the model due to the limitations of HEC-RAS 6.2 to work with a number of cells bigger than 500 000, to improve the accuracy of the model Break lines with 100 m spacing along the Santa Catarina River were included. The 4 reaches obtained from the HEC-HMS model were used as border conditions along the Santa Catarina River with the calibrated discharges as inputs. 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 layers, in the watershed. Also, classification polygons were created in the Land Cover and Infiltration layers along the mainstream of the Santa Catarina River with the Manning number (N_m) as parameter to calibrate the model and 100 % as percent of impervious. Figure 6 shows the schematic of the HEC-RAS model of the Santa Catarina River Watershed. A Weir with a culvert and spillway in the Rompepicos Dam location and 39 bridges were located by Google Maps (Google Map©, 2022) are included in the model.

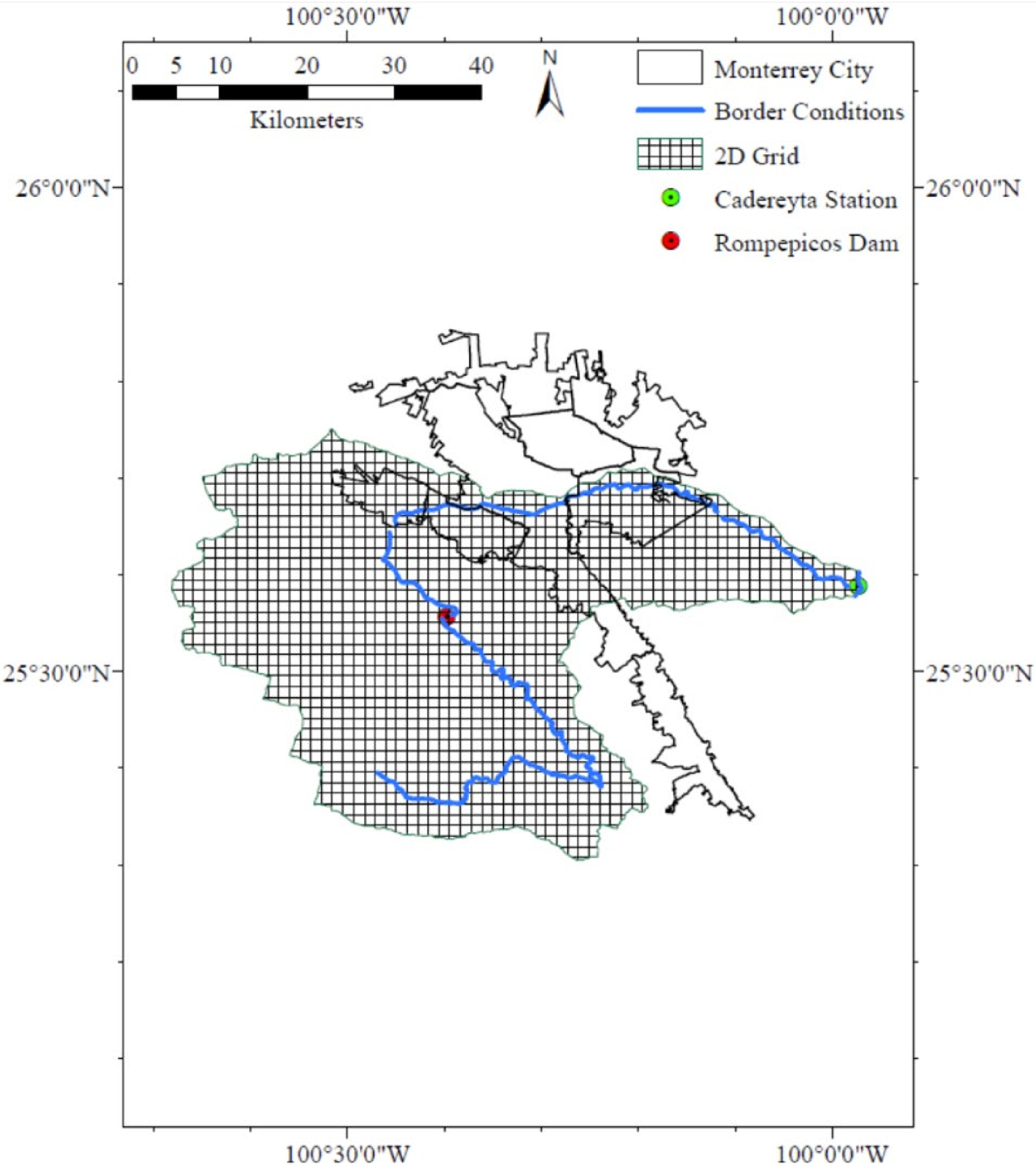

Figure 6. Schematic of the HEC-RAS model.

The simulated stages of the HEC-RAS 2D model were calibrated from 07/30/2010 17:00 AM to 07/05/2010 17:00 PM with observed stages at Cadereyta hydrometric station, the optimized values of the simulated stages against the observed have a r^2 of 0.74 and NS of 0.68. The Manning's number obtained for the calibration was N_m = 0.02, corresponding to pit and gravel for the whole stream. Figure 7 shows the observed and simulated stages after calibration of the HEC-RAS 2D model.

Figure 7. Observed and simulated stages at Cadereyta hydrometric station.

Table 6 summarize the results obtained after calibration of the HEC-HMS and HEC-RAS models against observed discharges and stages from 06/30/2010 17:00 to 07/05/2010 17:00 at Cadereyta.

Table 6. Observed and simulated peak and accumulated discharges and stages.

Parameter	Observed	Simulated
Peak discharge (m^3/s)	4310.6	4215.9
Acc. discharges (m^3)	74960.2	75318.2
Peak stage (m)	9.0	6.86

Table 7 summarize the observed maximum, minimum, median, mean, skewness and standard deviation discharges and stages used data at Cadereyta hydrometric station.

Table 7. Observed maximum, minimum, median, mean, skewness and standard deviation discharges and stages.

Parameter	Discharges	Stages
	(m^3/s)	**(m)**
Maximum	4 310.6	9.0
Minimum	0.0	0.0
Median	1 514.9	2.64
Mean	1 839.1	2.68
Skew	0.18	0.61
Standard deviation	1 510.1	1.41

Table 8 summarizes the r^2 and Nash-Sutcliffe coefficients obtained after calibration of the HEC-HMS and HEC-RAS 2D models against observed discharges and stages from 06/30/2010 17:00 to 07/05/2010 17:00 at Cadereyta.

Table 8. r^2 and Nash-Sutcliffe (NS), RMSE and MAE coefficients.

Coefficients	Discharges	Acc. discharges	Stages
r^2	0.97	0.99	0.74
NS	0.97	1.00	0.68
RMSE	0.22	0.11	0.58
MAE	3.21	2.19	4.16

A RMSE of 0.22, 0.11, 0.58 and a MAE of 3.21, 2.19 and 4.16 for the simulated and accumulated discharges and stages respectively. The r^2, NS, MRSE and MAE indexes show satisfactory results for the calibrated discharges, meanwhile a very good result for the calibrated stages.

Figure 8 shows the Flood map of the Santa Catarina River simulated corresponding to the maximum inundation area obtained at 07/02/2010 02:00.

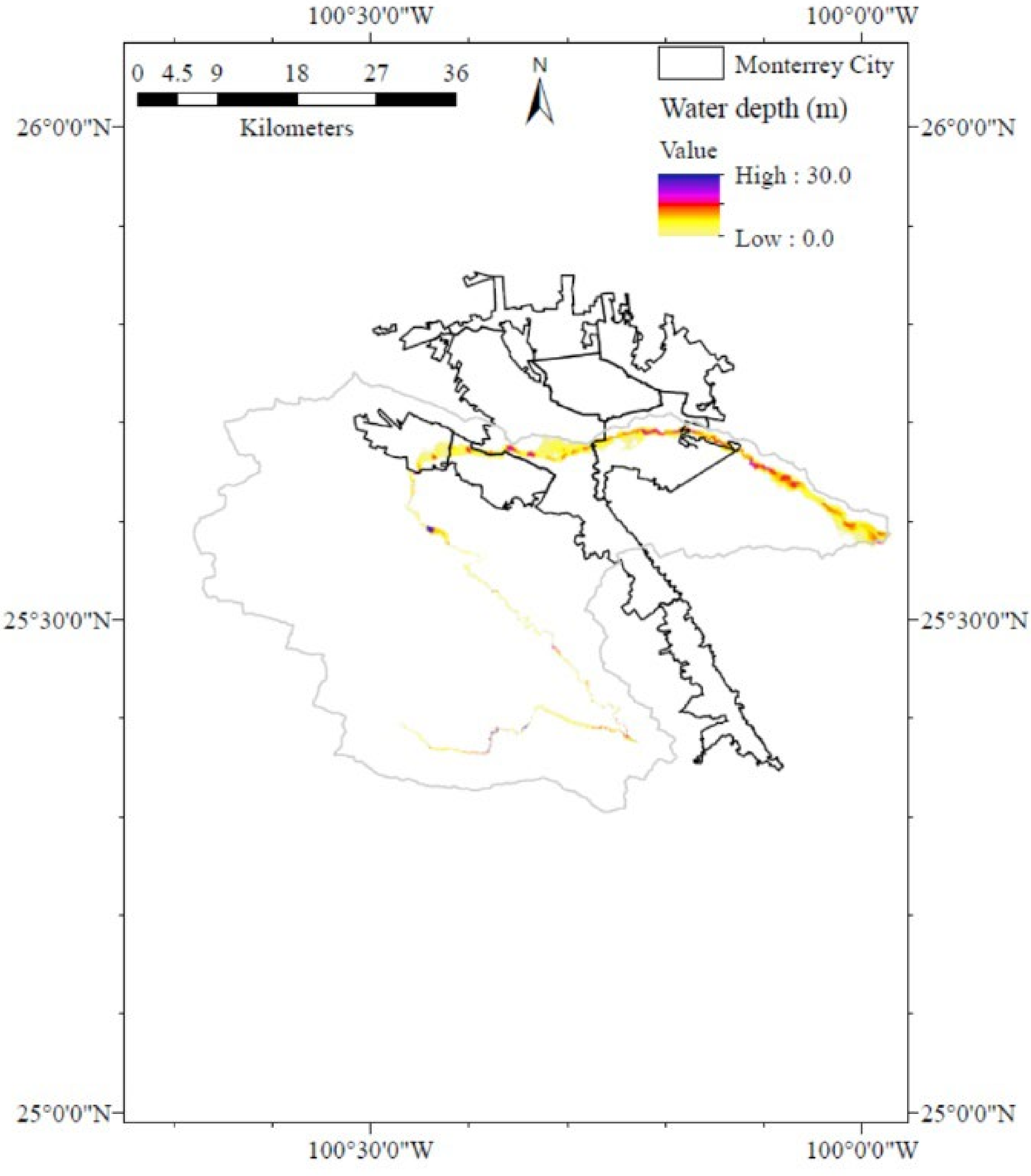

Figure 8. Flood map simulated.

Table 9 summarize the simulated maximum flood area; water depth and water velocity were obtained in the Santa Catarina River watershed from 06/30/2010 17:00 to 07/05/2010 17:00.

Table 9. Maximum simulated flood area, water depth, velocity, peak flow, and stage.

Parameter	**Value**
Maximum flood area (km^2)	40.45
Maximum water depth (m)	29.57
Maximum water velocity (m/s)	4.75

Based on this information, the results from the calibration and validation of the HEC-HMS and HEC-RAS models for the Santa Catarina River watershed shows:

- The HEC-HMS model was calibrated using observed discharges at the Cadereyta hydrometric station from June 30, 2010, to July 5, 2010.The calibration yielded an r^2 of 0.97 and Nash-Sutcliffe Efficiency (NS) of 0.97 for simulated discharges, indicating a very good fit between simulated and observed values. Accumulated discharges also showed a high correlation (r^2 = 0.99, NS = 1.00, RMSE = and MAE =), suggesting the model accurately captured the total runoff volume over the calibration period. Peak discharge simulations were slightly lower than observed, with a peak discharge of 4 215.9 m^3/s compared to an observed 4 310.6 m^3/s, but still within a reasonable range.

- A HEC-RAS 2D model was developed for the watershed using a 1-meter resolution DEM and included detailed features such as break lines along the Santa Catarina River. The model was calibrated using observed stages, resulting in an r^2 of 0.74 and NS of 0.68. This indicates moderate agreement between simulated and observed stages, suggesting some room for improvement in stage predictions. The Manning's number (Nm) for calibration was determined as 0.02, corresponding to pit and gravel conditions throughout the stream.
- Evaluation metrics such as Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) were used to assess model performance:
  - For discharges: RMSE = 0.22 and MAE = 3.21
  - For accumulated discharges: RMSE = 0.11 and MAE = 2.19
  - For stages: RMSE = 0.58 and MAE = 4.16

These metrics show that while discharges and accumulated discharges were well simulated with low errors, stage predictions had higher errors, especially in terms of RMSE and MAE.

- The maximum simulated flood area was 40.45 km², with a maximum water depth of 29.57 m and a maximum water velocity of 4.75 m/s during the simulated period. These outputs provide insights into the potential extent and severity of flooding under the simulated conditions, aiding in flood risk assessment and mitigation planning.

The overall assessment of the study shows that the HEC-HMS model demonstrated excellent performance in simulating discharges and accumulated discharges, with high correlation coefficients and low error metrics. The HEC-RAS 2D model, while useful for spatial flood analysis, showed moderate agreement in stage simulations, suggesting areas for further refinement, possibly through adjustments in model parameters or input data. In conclusion, the calibrated HEC-HMS and HEC-RAS models provide valuable tools for hydrological and hydraulic modeling in the Santa Catarina River watershed. They offer insights into flow dynamics, flood extents, and potential risks, although ongoing refinement and validation against additional data would enhance their reliability for future applications.

Conclusions

This paper presents a methodology to simulate floods along the mainstream of the Santa Catarina River watershed during the event Alex hurricane.

A HEC-HMS model was developed using Multi Radar Multi Sensor-Quantitative Precipitation Estimation as input to simulate discharges along the Santa Catarina River. The simulated discharges were calibrated using observed peak and accumulated discharges at Cadereyta Hydrometric Station, with the Curve Number as calibration parameter.

The calibrated HEC-HMS model achieved a simulated peak discharge of 4 215.9 against an observed of 4 310.6 m^3/s and simulated accumulated discharges of 75 318.2 against an observed of 74 960.2 m^3.

The observed against the simulated peak discharges achieved a r^2 of 0.97 a Nash-Sutcliffe coefficient of 0.97 a RMSE of 0.22 and a MAE of 3.21. The observed against the simulated accumulated discharges achieved a r^2 of 0.99 and a Nash-Sutcliffe coefficient of 1.0, a RMSE of 0.11 and a MAE of 2.19.

The r^2 and Nash-Sutcliffe coefficient results for the peak and accumulated discharges are very close to 1 showing that the HEC-HMS model have a high degree of accuracy after calibration.

The simulated discharges were introduced as border conditions along the mainstream of the Santa Catarina River inside the HEC-RAS 2D model grid, the simulated stages were calibrated using observed stages at Cadereyta Hydrometric Station, with Manning number as calibration parameter.

The calibrated HEC-RAS 2D model achieved a simulated peak stage of 6.86 against an observed of 9.0 m.

The observed against the simulated stages achieved a r^2 of 0.74 and, a Nash-Sutcliffe coefficient of 0.68, the RMSE is 0.58 and MAE 4.16.

The r^2 and Nash-Sutcliffe coefficient results for the peak stages are over 0.68 showing satisfactory results for the HEC-RAS model.

The novelty of this research lies in several key aspects:

1. The study employs both HEC-HMS and two-dimensional (2D) HEC-RAS models, demonstrating their combined effectiveness in simulating flood events. This dual-model approach provides a more comprehensive understanding of flood dynamics.
2. The research utilizes Multi-Radar Multi-Sensor-Quantitative Precipitation Estimation (MRMS-QPE) data to force the models. This integration is innovative because MRMS-QPE data offers high-resolution precipitation estimates, enhancing the accuracy of the hydrologic and hydraulic simulations.

3. The study achieves high accuracy in its simulations, with r^2 values of 0.97 and 0.99 and Nash-Sutcliffe coefficients of 0.97 and 1.0 for peak and accumulated discharges, respectively. This level of accuracy demonstrates the effectiveness of the methodology and the reliability of the models used.
4. Simulating a flood map along the entire mainstream of the Santa Catarina River, the study provides a detailed and practical tool for flood hazard assessment. This comprehensive mapping is crucial for risk management and urban planning in flood-prone areas.
5. The research highlights the user-friendliness and stability of the HEC-HMS and HEC-RAS 2D models, making them accessible for practical applications in flood management.

Overall, the novelty of this research lies in its methodological advancements, integration of high-resolution precipitation data, and the high accuracy of its flood simulations, providing valuable insights and tools for flood hazard assessment and management.

The methodology and findings of this research lies in the next aspects:

1. The process to design HEC-HMS and HEC-RAS 2D models coupled with MRMS-QPE precipitation is user-friendly to set up, stable, and capable of simulating flood maps along the entire mainstream of the Santa Catarina River with a good degree of accuracy.
2. One of the most important challenges in discharge simulation is that hydrologic and hydraulic models require high-quality spatial data. The use of high-resolution DEM and MRMS-QPE precipitation is critical for achieving high accuracy. The chosen grid size (500 m) limits accuracy,

and the lack of precise stage measurements during the event affects the results of the HEC-RAS model.

3. The successful incorporation of streams from the HEC-HMS model as boundary conditions in the HEC-RAS 2D model shows that this methodology can be generalized for more detailed watersheds. This methodology maximizes the strengths of each model: HEC-HMS simulates precipitation-runoff processes, and HEC-RAS simulates channel stages.
4. The current model can be refined by incorporating a higher resolution grid in the HEC-RAS 2D model, including a greater number of reaches and boundary conditions.
5. The methodology used in this study can be applied to flood map simulations and generalized for other applications, such as assessing environmental impacts. These applications are supported by tools available in the HEC-HMS and HEC-RAS software.
6. The methodology requires the use of HEC-HMS, HEC-RAS software, DEM, land cover and soil information with high resolution, and MRMS-QPE precipitation with short time steps. While HEC-HMS and HEC-RAS are open-source software, the DEM and MRMS-QPE data were obtained from U.S. sources that cover northeast Mexico. High-accuracy data for hydrologic applications are available in only a few countries, and any future application of this methodology in South America will require similarly accurate data.

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