Atmósfera 38, 79-89 (2024)
https://doi.org/10.20937/ATM.53234

Modeling tropical storm Elsa: Flood map simulation using multisensory precipitation in Connecticut

Juan M. STELLA

Department of Civil and Environmental Engineering, Lamar University, Beaumont, 77710, Texas, USA.
E-mail: jstella@lamar.edu

Received: September 29, 2022; accepted: February 22, 2023

RESUMEN

Se realizó una simulación de mapa de inundación en la cuenca del río Fenton, Connecticut, para la tormenta tropical Elsa ocurrida a inicios de julio de 2021. Se utilizó para ello el método multirradar/multisensor-estimación cuantitativa de la precipitación (MRMS-QPE, por sus siglas en inglés) como dato para aplicar el Sistema de Modelación Hidrológica del Centro de Ingeniería Hidrológica (HEC-HMS) para simular descargas en la corriente principal de la cuenca. Las descargas simuladas se calibraron utilizando las descargas observadas en la estación hidrográfica del puente Old Turnpike y se aplicaron a un Sistema 2D de Modelación Fluvial del Centro de Ingeniería Hidrológica (HEC-RAS) de la cuenca del río Fenton. Las alturas simuladas se calibraron usando las alturas observadas en la estación del Servicio Geológico de Estados Unidos del puente Old Turnpike con el fin de simular mapas de inundación en la corriente principal de la cuenca. El uso de los modelos 2D HEC-HMS y HEC-RAS junto con la precipitación MRMS-QPE muestra que estos modelos son fáciles de configurar. El modelo muestra estabilidad y capacidad para simular mapas de inundación a lo largo de toda la corriente principal del río Fenton con buena precisión.

ABSTRACT

A flood map simulation in the Fenton River watershed, Connecticut, was conducted for Tropical Storm Elsa occurred in early July 2021, using Multi Radar Multi Sensor-Quantitative Precipitation Estimation (MRMS-QPE) as input to force the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) to simulate discharges in the mainstream of the watershed. The simulated discharges were calibrated using observed discharges at the Old Turnpike Bridge USGS station, and they were used to force a Hydrologic Engineering Center-River Analysis System (HEC-RAS) 2D model of the Fenton River watershed. The simulated stages were calibrated using observed stages at Old Turnpike Bridge USGS station to simulate flood maps in the mainstream of the watershed. The resulting use of HEC-HMS and HEC-RAS 2D models coupled with MRMS-QPE precipitation shows that these models set up is user-friendly. The model shows stability and the capacity to simulate flood maps along the whole mainstream of the Fenton River with good accuracy.

Keywords: MRMS-QPE precipitation, HEC-HMS, HEC-RAS 2D, floodmap, New England.

1. Introduction

Tropical Storm Elsa moved north parallel to the west coast of Florida (Lodge and Weaver, 2022) and hit the US east coast by early July 2021 (Strypsteen et al., 2022). Very much like other storms, Elsa was responsible for creating destruction, economic losses, and mortality (Teng et al., 2017; Mihu-Pintilie et al., 2019).

Tropical Storm Elsa was responsible for floods, one of the most frequent and disruptive natural hazards (Alfonso et al., 2016). Flood hazard assessment and flood mapping applying flood inundation models to identify flood risk zones can be the first steps to apply flood mitigation measures (Mihu-Pintilie et al., 2019; Patel et al., 2017; Shustikova et al., 2019).

Since the beginning the 21st century flood hazard mapping has undergone significant development and is a vital tool in flood hazard and risk management analysis (Mudashiru et al., 2021). The primary tools for performing inundation mapping are hydraulic and hydrologic models to simulate discharges and flood events, search for vulnerable areas, and create a flood management plan (Mihu-Pintilie et al., 2019). The use of hydraulic models such as HEC-RAS, Tuflow, and Mike series for carrying out flood simulations and flood mapping is a common practice globally (Ongdas et al., 2020). But hydrologic and hydraulic models require high-quality spatial data, especially a continuous representation of precipitation for the hydrologic models, so remote sensor input is critical to achieving this continuity (Kitzmiller et al., 2013).

Since the end of the 20th century, there has been a focus on developing new applications and systems to address requirements for quantitative precipitation estimation, with multiple overlapping radars or remote sensing observations and numerical weather predictions (NWP) (Droegemeier et al., 2002; Kelleher et al., 2007). The National Oceanic and Atmospheric Administration's (NOAA, 2022) current capabilities are produced using the Multi-Radar Multi-Sensor-Quantitative Precipitation Estimation (MRMS-QPE) system, which is a real-time, multisensory precipitation system that can provide input to hydrologic models using a grid mesh of 1 km with a 5-min time step and minimal time lag from the real event. This system has been operating since 1997, when the NEXRAD network was deployed (Zhang et al., 2013; NOAA, 2022; Kitzmiller et al., 2013). The Iowa Environmental Mesonet (ISU, 2022) collects environmental data such as precipitation, solar radiation, and wind from cooperating members with observing networks and maintains an archive of the MRMS-QPE project for public use (ISU, 2022).

The United States Army Corps of Engineers (USACE, 2022) models, such as the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) and River Analysis System (HEC-RAS) have become essential tools for hydrologic modeling, hydraulic design, and water management. They are widely used in numerous studies and applications and can perform unique functions (Halwatura and Najim, 2013). Also, these models can be linked to the simulation of major storm events (García et al., 2020).

HEC-HMS was designed to simulate the precipitation-runoff processes of dendritic watershed systems (USACE, 2022. The model can be applied to a wide range of geographic areas for solving a broad range of problems, such as large river basin water supply, and flood hydrology for a small urban or natural watershed (Halwatura and Najim, 2013), with the simulation of surface runoff and peak discharges in the watershed (Chu and Steinman, 2009). The result of the modeling process is the computation of stream flow hydrographs at the watershed outlet (Oleyiblo and Li, 2010).

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

Thakur et al. (2017) applied HEC-HMS and one-dimensional HEC-RAS (1D) models coupled with gage precipitation in the Copper Slough Watershed, Illinois. They found that forcing the HEC-HMS model with forecasted precipitation can work as a flood warning system by generating pre-flood inundation maps with HEC-RAS 1D. Stella (2022) applied a HEC-RAS 1D model forced with observed and simulated discharge in the Fenton River watershed during the 1955, 2005 and 2008 storms to simulate flood maps downstream the Old Turnpike Bridge. Knebl et al. (2005) applied HEC-HMS and HEC-RAS 1D models coupled with Next Generation Weather Radar (NEXRAD) precipitation in the San Antonio River watershed, Texas. The flood maps obtained from the simulation are comparable to satellite imagery, showing that HEC-RAS 1D is a very good tool for hydrological forecasts of flooding.

Vozinaki et al. (2017) research concluded that the combined HEC-RAS 1D/2D model performs better than the HEC-RAS 1D model when topographic data at high spatial resolution are used. The combination of 1D-2D HEC-RAS flood modeling allows the channel flows to be represented in 1D and the overbank flow to be modeled in 2D (Dasallas et al., 2019).

Brunner et al. (2015) considered that HEC-RAS 2D is a flexible model for complex hydraulic systems and can work with subcritical, supercritical, and mixed flow regimes; moreover, the property tables allow for a more accurate representation of the terrain to get accurate results. Dasallas et al. (2019) reported that the HEC-RAS 2D model consistently outperformed HEC-RAS 1D and HEC-RAS 1D-2D models. Ghimire et al. (2022) considered that the HEC-RAS 1D model failed to provide detailed two-dimensional information for the floodplain area, compared with the results from HEC-RAS 1D/2D model. The disadvantage of the 2D model is that it requires substantial computational time and a high computational grid (Vozinaki et al., 2017).

This study describes an alternative modeling method to HEC-RAS 1D-2D applying a full HEC-RAS 2D with internal border conditions along the mainstream as input for the discharges of a flood event during tropical storm Elsa in early July, 2021, in Northwest Connecticut, New England. The study area selected for model development was the Fenton River Watershed (an ungauged stream up to 2006) during tropical storm Elsa. This was the biggest stream flow discharge recorded in this location (USGS, 2022a). A flood map of the Fenton River was generated by applying first a HEC-HMS model to simulate discharges in the watershed forced by MRMS-QPE precipitation and then a two-dimensional HEC-RAS 2D model forced with the discharges obtained from HEC-HMS as border conditions inside the HEC-RAS 2D grid.

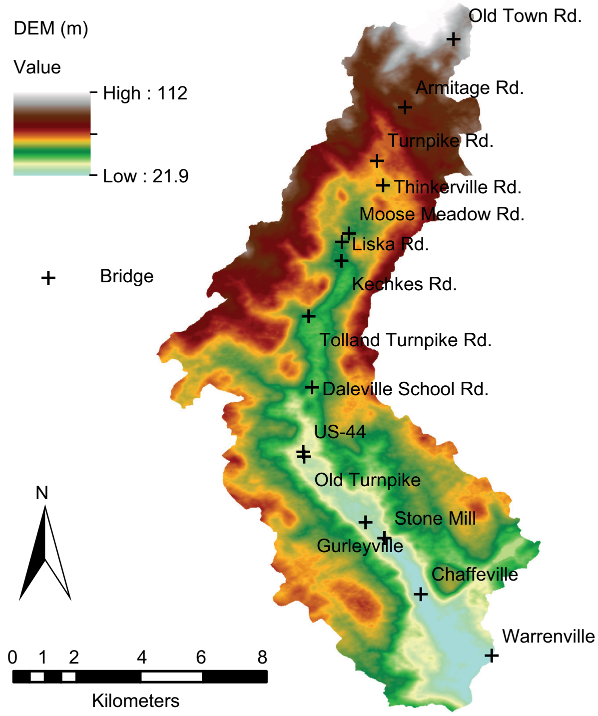

Fig. 1. Fenton River watershed and bridges across the mainstream of the river.

Table I. Maximum, minimum and mean yearly precipitation and discharges.

Parameter	Unit	Minimum	Maximum	Mean
Precipitation	mm	787	1627	1138
Discharges	$m^3 s^{-1}$	0.0068	23.4	0.96

2. Materials and methods

2.1 Characteristics of the watersheds

The Fenton River has a total length of 23 km and a drainage area of 89 km^2 as it enters Mansfield Hollow Lake and since October, 2006 it has a gauging station for the estimation of daily stream flow discharges, located at Old Turnpike Bridge (United States Geological Survey [USGS] gage 01121330, Tolland County, 41º 49’ 59.50” N, 72º 14’ 34.01” NAD83), with a drainage area of 47.4 km^2 (USGS, 2022a). Figure 1 shows the Fenton River and bridges across the mainstream. Table I summarizes the yearly minimum, maximum, and mean precipitation in Connecticut and discharges in the Fenton River (Miller et al., 2002; USGS, 2022a).

There are 15 bridges and culverts along the Fenton River mainstream from Old Town Road to the outlet of the stream at Warrenville Road: Old Town, Armitage, Turnpike, Thinkerville, Moose Meadow, Liska, Kechkes Tolland Turnpike, Daleville School, US-44, Old Turnpike, Gurleyville, Stone Mill, Chaffeville and Warrenville (Bridges Report, 2022). The total drainage area of the Fenton River where the flood map will be simulated is 89 km^2, and the drainage area of the Fenton River upstream Old Turnpike Bridge is 47.4 km^2.

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

Data for the application of HEC-HMS and HEC-RAS 2D models such as data from the Digital Elevation Model (DEM) were obtained from the USGS

(2022b) with a 1 × 1 m resolution, land cover from the National Land Cover Database (NLCD, 2022), and soil type from the United States Department of Agriculture (USDA, 2022), both with 30 × 30 m resolution, all through ArcGIS online (ESRI). Discharges and stages were obtained from the USGS at Old Turnpike Bridge (USGS, 2022a) with a 15 min time step and grid precipitation from Mesonet (IEM, 2022) with a 4000 m resolution and 1 h time step. Table II summarizes the sources of data. The HEC-RAS 2D model grid has a 100 × 100 m resolution and 10 s time step.

2.3 Evaluation coefficients

The observed discharges and stages of Fenton River at Old Turnpike Bridge were used to conduct the calibration of HEC-HMS and HEC-RAS 2D by applying the evaluation coefficients R-squared (r^2), Nash-Sutcliffe (NS) model of efficiency, root mean square error (RMSE) by the standard deviation of observations, and mean absolute error (MAE).

The R-squared regression coefficient of determination (equation 1) is the most used statistics to assess the degree of fit of a model. It measures the trend line variation (Akossou and Palm, 2013).

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

where SCE_p is the sum of squares related to the regression, and SCE_{tot} is the total sum of squares.

The NS model of efficiency is given by equation 2 (Nash and Sutcliffe, 1970).

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

where O_i are the observed discharges, $\bar{O}$ is the mean of the observed discharges, S_i are the simulated discharges, and n is the number of steps modeled.

RMSE by the standard deviation of observations is given by equation 3 (da Silva et al., 2015).

$$RMSE = \frac{\sqrt{\sum_{i=1}^{n} (O_i - S_i)^2}}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O}_i)^2}} \qquad (3)$$

The MAE of observations is given by equation 4 (Willmott and Matsuura, 2005).

$$MAE = \frac{\sum_{i=1}^{n} abs(S_i - O_i)}{n} \qquad (4)$$

Table III summarizes the coefficient evaluation criteria for R-squared (r^2), NS, and RMSE according to da Silva et al. (2015) and Chicco et al. (2021).

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

Data	Data source
DEM	United States Geological Survey (USGS, 2022b) https://viewer.nationalmap.gov/basic/ with ArcGIS online
Land cover	National Land Cover Database (NLCD, 2022) www.mrlc.gov with ArcGIS online
Soil type	Soil Survey Geographic Database (USDA, 2022) http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx with ArcGIS online
Precipitation	Iowa Environmental Mesonet (IEM, 2022) https://mesonet.agron.iastate.edu/
Discharges and stages	United States Geological Survey (USGS, 2022a) https://waterdata.usgs.gov/usa/nwis/uv?01121330

DEM: Digital Elevation Model.

Table III. Criteria for evaluating the performance of the hydrological model,

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

3. Results and discussion

An HEC-HMS model was designed for the Fenton River watershed with a 1 m DEM resolution and NAD83 projection. The model delivered 17 subbasins, eight reaches, and one sink as outlets. The HEC-HMS project includes the following components for subbasins: projection, basin, meteorological models, control specifications, and grid and terrain data. Table IV summarizes the HEC-HMS processes.

The functions selected to run subbasin processes were loss with SCS Curve number, transform with SCS Unit Hydrograph, base flow with recession, and routing with Muskingum. For reaches, the HEC-HMS project includes the component routing with Muskingum. Tables V and VI summarize the parameters of the watershed before and after calibration.

The simulated discharges of the HEC-HMS model were calibrated from 08:45 LT on 07/09/2021 to 14:45 LT on 07/10/2021 with the observed discharges in the Old Turnpike Bridge. The optimized values of simulated discharges against the observed ones using Curve number (CN) values as calibration parameters have an R-squared of 0.87 and NS of 0.59. Figure 2 shows the observed and simulated discharges after the calibration of the HEC-HMS model. Even though the relationship between observed and simulated discharges is satisfactory, Figure 2 shows a nonlinear relationship between the observed and simulated discharges. The event has twin peak discharges during the storm, so the calibration was focused on the second (largest) peak discharge.

An HEC-RAS 2D model was designed for the Fenton River watershed with a 1 m DEM resolution, with an RMSE of 0.10 RMSE, a 100 × 100 m grid, and NAD83/Connecticut (ftUS) projection. The eight reaches obtained from the HEC-HMS model were used

Table IV. HEC-HMS project processes.

Component	Process
Basin model	17 Subbasins, 8 reaches and 1 sink
Meteorological model	Gridded precipitation
Control specifications	From 07/08/2021 00:00 to 07/12/2021 23:15
Grid data	MRMS-QPE Precipitation
Terrain data	DEM 1-meter resolution
Projection	NAD83/Connecticut (ftUS)

Table V. Parameters of the subbasins model before and after calibration.

Subbasin #	Initial abstraction (mm)		Curve number (-)		Impervious (%)		Lag time (min)	
	Before	After	Before	After	Before	After	Before	After
1	0.5	0.5	76	85	0	50	414.0	311.1
2	0.5	0.5	76	85	0	50	234.4	176.1
3	0.5	0.5	78	85	0	50	238.8	238.8
4	0.5	0.5	79	85	0	50	181.4	301.6
5	0.5	0.5	75	85	0	50	266.6	149.1
6	0.5	0.5	82	82	0	0	190.6	190.6
7	0.5	0.5	82	82	0	0	29.7	29.7
8	0.5	0.5	82	82	0	0	355.3	355.3
9	0.5	0.5	84	84	0	0	147.6	147.6
10	0.5	0.5	79	85	0	50	175.6	190.4
11	0.5	0.5	79	85	0	50	366.9	144.4
12	0.5	0.5	80	85	0	50	277.2	277.2
13	0.5	0.5	85	85	0	0	272.3	272.3
14	0.5	0.5	82	82	0	0	232.1	232.1
15	0.5	0.5	75	75	0	0	463.5	463.5
16	0.5	0.5	81	81	0	0	192.1	192.1
17	0.5	0.5	85	85	0	0	53.2	53.2

Table VI. Parameters of the reaches model before and after calibration.

Reach (-)	Muskingum k (h)		Muskingum X (-)		# Sub reaches (-)	
	Before	After	Before	After	Before	After
1	0.5	0.5	0.25	0.25	1	1
2	0.5	0.5	0.25	0.25	1	1
3	0.5	0.5	0.25	0.25	1	1
4	0.5	0.5	0.25	0.25	1	1
5	0.5	0.5	0.25	0.25	1	1
6	0.5	0.5	0.25	0.25	1	1
7	0.5	0.5	0.25	0.25	1	1
8	0.5	0.5	0.25	0.25	1	1

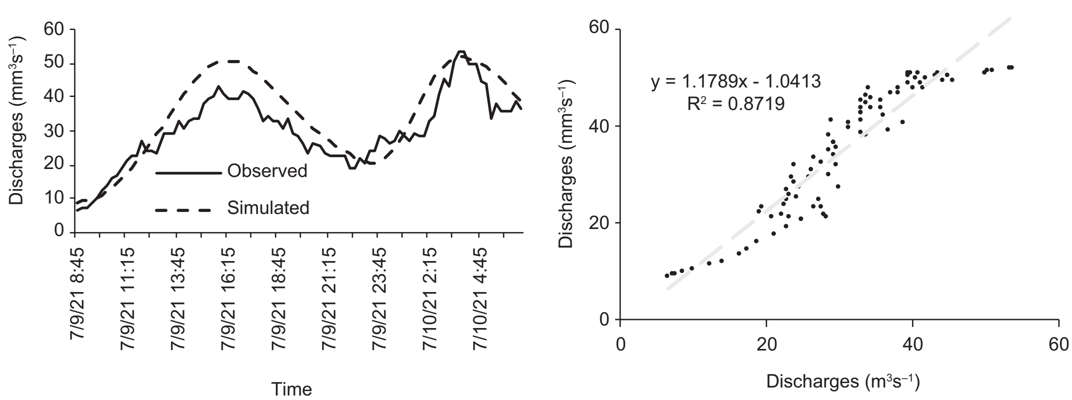

Fig. 2. Observed and simulated discharges by HEC-HMS model at Old Turnpike Bridge.

as border conditions inside the HEC-RAS 2D grid with the calibrated discharges as inputs. Land cover and soil layers were used as input to obtain the CN, Manning number (N_m), Abstraction Ratio, Infiltration Rate, and Percent of Impervious Land layers, in the watershed. A special area was created in the mainstream of the Fenton River and was used for calibration with the N_m as a parameter to calibrate the model.

The simulated stages of the HEC-RAS 2D model were calibrated from 08:45 LT on 07/09/2021 to 14:45 LT on 07/10/2021 with observed stages at Old Turnpike Bridge. The optimized values of the simulated stages against the observed ones have an R-squared of 0.85 and NS of 0.96. The N_m obtained for the calibration was = 0.035, corresponding to pit and gravel for the whole stream. Figure 3 shows the observed and simulated stages after calibration of the HEC-RAS 2D model.

In summary, figure 4 shows the schematics of the HEC-HMS and HEC- RAS 2D models, as well as the flood map obtained from the simulation forced by MRMS-QPE precipitation. The HEC-HMS model includes the 17 subbasins and eight reaches, while the HEC-RAS 2D model includes the 100 × 100 grid and the mainstream of the river zone for the calibration, with the flood map corresponding to the maximum inundation area obtained at 03:45 LT on 07/10/2021 with a DEM as background.

Table VII summarizes the peak flow and stage for the simulated values after calibration of the HEC-HMS and HEC-RAS 2D models at Old Turnpike Bridge. Table VIII summarizes the R^2, Nash-Sutcliffe, RMSE and MAE coefficients obtained after calibration of the HEC-HMS and HEC-RAS 2D models against observed discharges and stages from 08:45 LT on 07/09/2021 to 16:00 LT on 07/10/2021. Table IX summarizes the simulated maximum flood area. Water depth and water velocity were obtained in the Fenton River watershed from 07/09/2021 to 10/10/2005.

4. Conclusions

This paper presents the methodology and development of a flood model in the Fenton River watershed, Connecticut. A simulation was conducted for tropical storm Elsa using MRMS-QPE as input to force an HEC-HMS model to simulate discharges in the mainstream of the watershed. The simulated discharges were calibrated using observed discharges at the Old Turnpike Bridge USGS station, with CN as the calibration parameter for every subbasin of the watershed.

The simulated discharges were used to force an HEC-RAS 2D model of the Fenton River watershed introduced as border conditions inside the 2D grid. The simulated stages were calibrated using observed stages at the Old Turnpike Bridge USGS station, with N_m as a calibration parameter to simulate flood maps in the mainstream of the watershed.

The HEC-HMS model forced with MRMS-QPE precipitation achieved a simulated peak discharge of 51.8 $m^3 s^{-1}$ against an observed of 53.5 $m^3 s^{-1}$. The HEC-RAS 2D model forced by HEC-HMS discharges achieved a simulated peak stage of 2.3 m against an observed of 2.4 m.

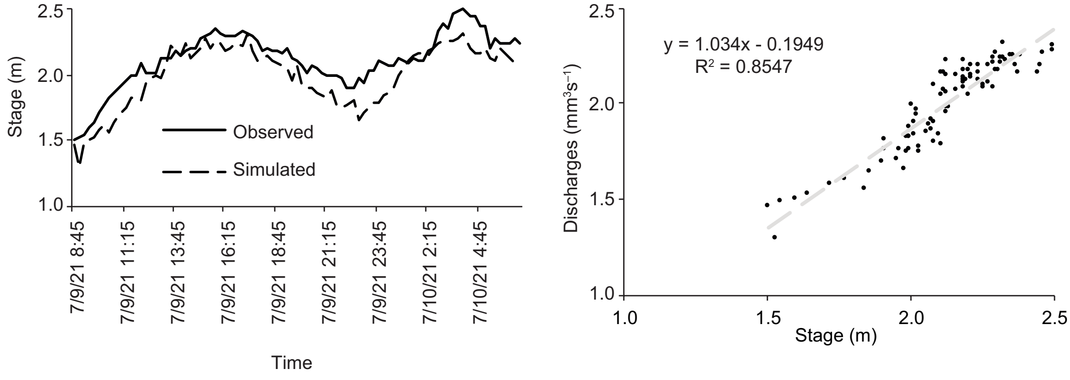

Fig. 3. Observed and simulated stages by HEC-RAS 2D model at Old Turnpike Bridge.

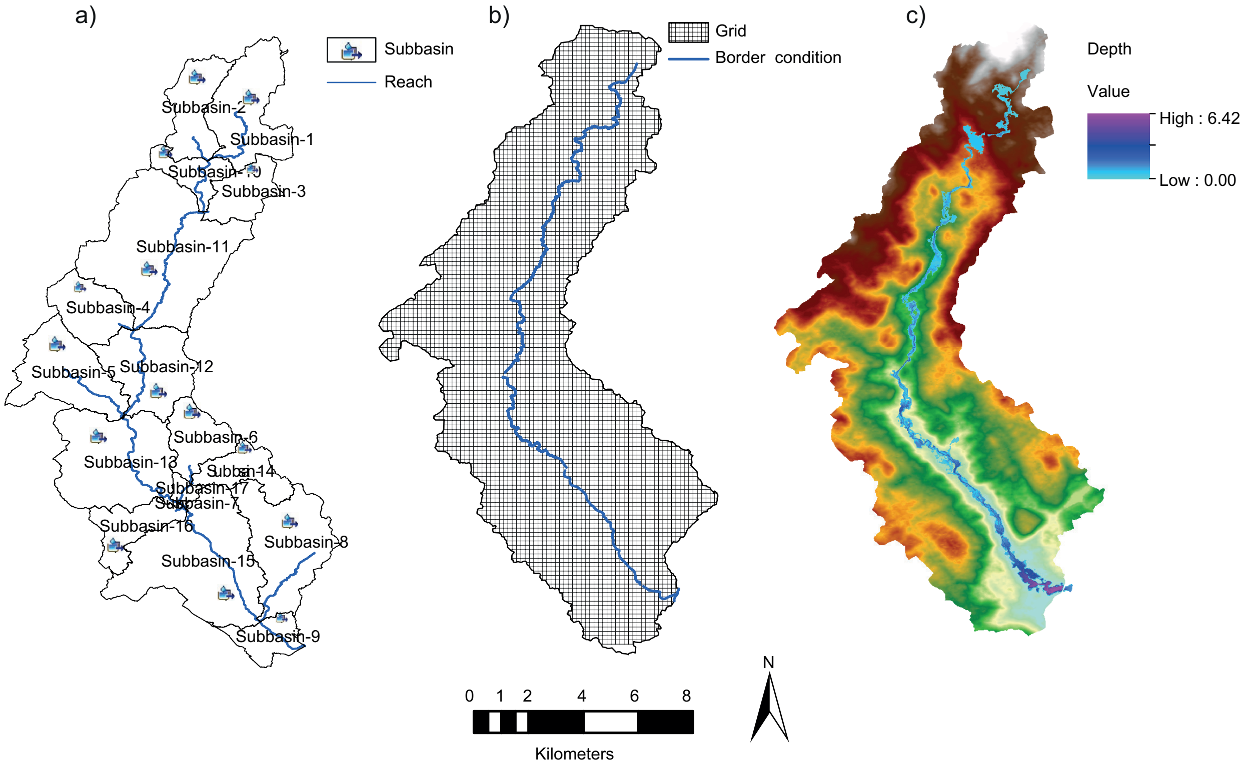

Fig. 4. Schematics of the (a) HEC-HMS, (b) HEC- RAS 2D models, and (c) simulated flood map.

Table VII. Peak flow and stages.

Parameter	Unit	Observed	Simulated
Peak flow	$m^3 s^{-1}$	53.5	51.8
Stage	m	2.4	2.3

Table VIII. R-squared (r^2), NS, RMSE and MAE coefficients.

Coefficients	Discharges	Stages
r^2	0.87	0.85
NS	0.59	0.96
RMSE	0.64	0.19
MAE	5.64	0.13

NS: Nash-Sutcliffe; RMSE: root mean square error; MAE: mean absolute error.

The resulting simulation achieved an R-squared of 0.87 and 0.85; an NS coefficient of 0.59 and 0.96; an RMSE of 0.64 and 0.19, and a MAE of 5.64 and 0.13 for the simulated discharges and stages, respectively. The R^2, NS, MRSE, and MAE indexes showed satisfactory results for the calibrated discharges, as well as a very good result for the calibrated stages.

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

Parameter	Unit	Value
Maximum flood area	km^2	4.84
Maximum water depth	m	6.42
Maximum water velocity	$m s^{-1}$	3.14

The process to design HEC-HMS and HEC-RAS 2D models coupled with MRMS-QPE precipitation has a user-friendly setup. The model shows stability and the capacity to simulate flood maps along the whole mainstream of the Fenton River with a high degree of accuracy.

One of the most important problems with the simulation of discharges is that hydrologic and hydraulic models require high-quality spatial data, the use of DEM, high-resolution land cover and soil, and MRMS-QPE precipitation, which can be critical to achieve a high degree of accuracy during the simulation.

The successful integration of streams from the HEC-HMS model as border conditions in the HEC-RAS 2D model demonstrates the potential for generalizing this methodology to more intricate watersheds. By combining the strengths of each model, with HEC-HMS handling precipitation-runoff processes and HEC-RAS managing channel stages, the approach maximizes the effectiveness of both models.

The current model can be refined by incorporating higher resolution data related with the tributaries to the mainstream in the HEC-RAS 2D model. An HEC-HMS model with a larger number of subbasins and reaches should be created, adding a larger number of border conditions and bridges to the HEC-RAS 2D model.

Acknowledgments

The author acknowledges the assistance of two anonymous reviewers for their contributions, which enriched this document.

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