A Flood Early Warning System Design and Implementation for the Rio Grande de Morelia Basin, Mexico

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Abstract: *This paper addresses flood risk management and the need for preventive measures to minimize flood impacts in the Rio Grande de Morelia basin, Mexico. Due to rapid population growth and limited urban planning, the city of Morelia faces recurring flood threats that cause significant damage to communities, infrastructure, and the environment. This research proposes the development of a Flood Early Warning System (FEWS) that integrates data monitoring across three levels, utilizing a hydrological model calibrated with a 0.77 correlation coefficient. Hydraulic modelling identified 878.87 hectares as high flood-risk areas. The results suggest that this methodology can structure an effective FEWS system for the Rio Grande de Morelia, enhancing flood prediction and mitigation capabilities through continuous system improvement, data expansion, and real-time monitoring.*

Keywords: *Flooding, hazard management, hydrological basin, early warning system, Rio Grande de Morelia*

1. Introduction

Flooding occurs when precipitation in a watershed generates runoff that surpasses the capacity of riverbeds to contain it, causing overflow. This excess water can inundate low-lying areas, impacting nearby populations and surroundings. In Mexico, numerous cities have developed along rivers and are frequently affected by floods. Yet, policies and response measures to address flooding are typically reactive, deployed either during or after events, and often fall short of significantly mitigating damage. This reactive approach underscores the need for a shift in disaster management—moving from a passive to a proactive stance that prioritizes risk management and preventive actions. Effective flood prevention and mitigation require understanding the origins and flooding behaviour, along with fostering community awareness and preparedness [1]
Flooding remains a serious issue in the city of Morelia, exacerbated by increasing runoff from rain and a reduced capacity for water evacuation due to narrowing of the Rio Grande-Chiquito River system, including its main drains and tributaries in both urban and agricultural areas. Between 2002 and 2017, 22 neighbourhoods in Morelia, comprising 25,811 residents in 6,212 homes, were designated as flood-prone, alongside 500 hectares of farmland in the Rio Grande floodplain [2]. Mitigating flood damage requires both structural measures (e.g., construction projects) and non-structural measures (institutional and policy-based interventions). For this study, the focus is on non-structural civil protection measures, including planning, organization, coordination, and execution of actions aimed at reducing flood impact [3]

1.1 Flood Early Warning Systems Worldwide

A Flood Early Warning System (FEWS) relies on observation networks to collect environmental data, particularly rainfall and flow metrics for flash flood situations. Rainfall data is gathered from in-situ measurement stations, radar systems, satellite estimates, or a combination of these methods. An effective EWS requires computer infrastructure to collect, analysed, and distribute data through alert systems and communication channels. When a preparedness plan is in place and the population is educated on flood risks, early warning alerts can prompt individuals to take protective actions, such as seeking shelter, safeguarding personal items, or securing property.

Examples of EWS implementations include the United States, where hydrometeorological bulletins provide national information, supported by local measurement systems. Italy’s Piedmont region employs a multidisciplinary Real-Time Flood Forecasting and ALERT system, while Colombia’s Aburrá Valley leverages radar information within its Early Warning System for Natural Hazards. These systems generally operate through four key stages: data input (collected from field sources), data processing (building a forecasting model), alert dissemination (determining and communicating alert indicators), and system feedback for continuous improvement [4].

2. Materials and Methods

2.1 Study Area

This paper was conducted at RH12Gb-Lake Cuitzeo sub-basin, where the Rio Grande de Morelia flows through into of urban area Morelia, Michoacán, Mexico. The study area spans from the upstream portion from Cointzio Dam to the river's mouth at Cuitzeo, Lake covering a basin area of 1,748 km² [5], as shown in Figure 1.

Fig. 1. Location of the RH12Gb-Lake Cuitzeo sub-basin, Michoacán, Mexico [5]

3. Methodology

Developing an Early Warning System (FEWS) for the city of Morelia in Michoacán, Mexico, is essential due to the city’s vulnerability to floods caused by heavy rains, particularly during the rainy and hurricane seasons. This type of system helps mitigate the risk of human and material losses through early detection and prompt response to potential flooding events. Below is an outline for implementing an effective EWS in Morelia.

A. Hydrometeorological Early Warning System (EWS) Operations:

The EWS operation integrates data from Automatic Meteorological Stations (EMAs), Automatic Hydrometric Stations (EHAs), and a central reception centre. This system consolidates data acquisition, hydrometeorological modelling, result analysis, and the issuance of alerts, as shown in Figure 2.

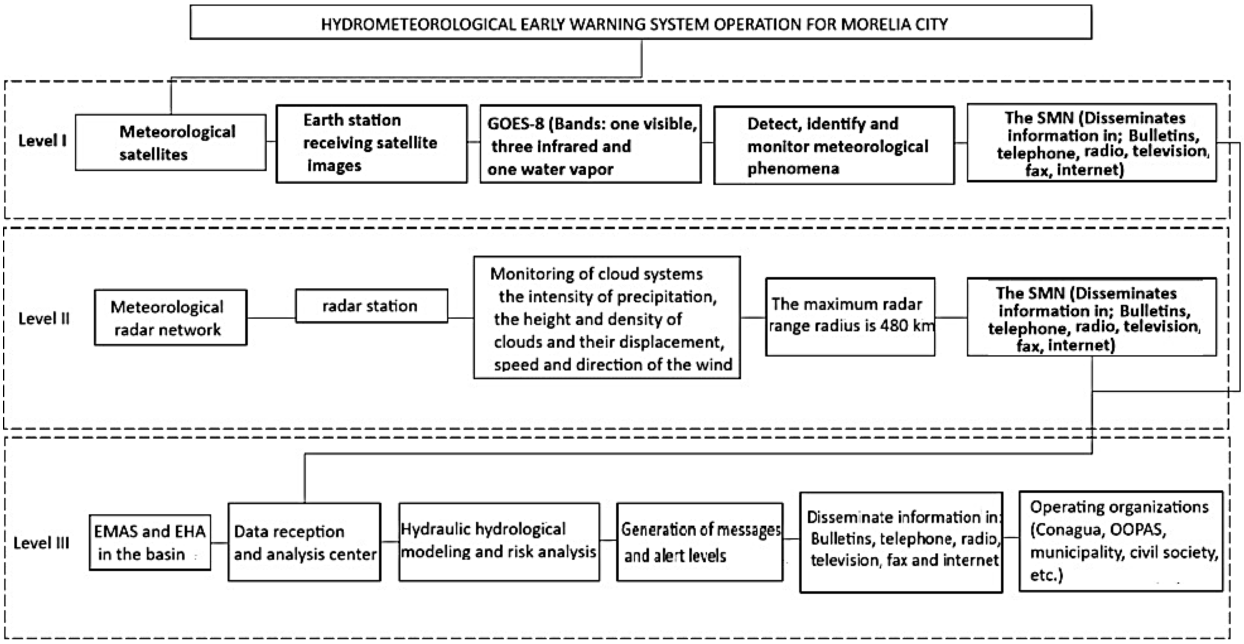

Fig. 2. Flood Early Warning System for Morelia. Source: Own design

B. Technical Organization

Key organizations involved in EWS operations and information dissemination include CONAGUA (National Meteorological Service), the Morelia Drinking Water, Sewerage, and Sanitation Agency (OOAPAS), civil protection agencies, media, educational institutions, private entities, and civil society.

C. Hydrometeorological Data Capture

The information reception centre aggregates data from meteorological and hydrometric stations, as well as satellite and radar feeds, to issue alarms for public protection. This centre comprises an interdisciplinary team responsible for informed decision-making.

D. Hydrological and Hydraulic Modelling

Hydrological simulations are initiated using HEC-HMS during critical weather events, utilizing input data from EMAs and EHAs, processed at 10-minute intervals. The output hydrographs are then inputted into the IBER hydraulic model, which generates flood envelope maps based on the water flow at sub-basin outflows.

E. Data Evaluation and Analysis

Following the modelling process, an evaluation phase compares simulation results with field data. This analysis assesses the progression of flood patterns and validates model results, as illustrated in Figure 3.

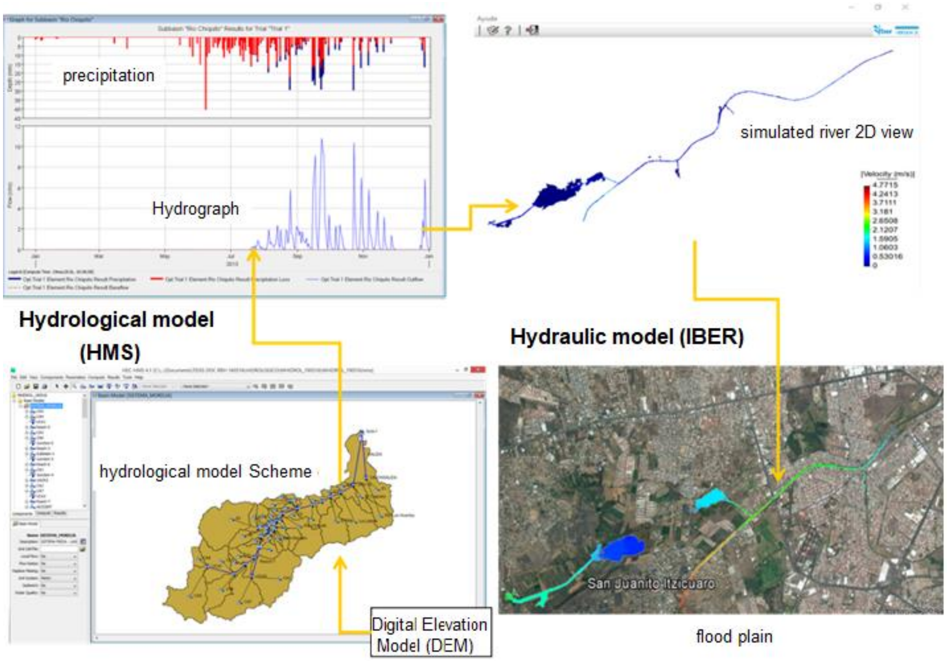

Fig. 3. Hydraulic simulation process using hydrological models

F. Issuance of Hydrometeorological Alerts

Flood risk alerts are issued in three levels during the rainy season:

Level I (Yellow): Initiates early warnings based on geostationary satellite (GOES) imagery. Data from visible, infrared, and water vapor channels covering North America are analyzed by the National Meteorological Service (SMN) and disseminated to relevant agencies.

Level II (Orange): Signals an imminent emergency based on continuous monitoring from 13 national radars. These radars provide real-time data on cloud systems, precipitation intensity, and wind conditions. The radar in Querétaro monitors the Morelia area, feeding back into Level I observations for updated alerts.

Level III (Red): Based on EWS data, it indicates an immediate flood threat when a tropical cyclone impacts the study area. This level incorporates information from automatic stations and GOES-based hourly updates to enable timely public warnings.

G. Level III EWS Operations for Morelia

Level III monitoring includes extensive data capture and model calibration to assess hydrometeorological threats. The system integrates hydrological [6] and hydraulic [7] models with topographic, soil, vegetation, meteorological, and hydrometric data, as depicted in the FEWS structural diagram in Figure 4.

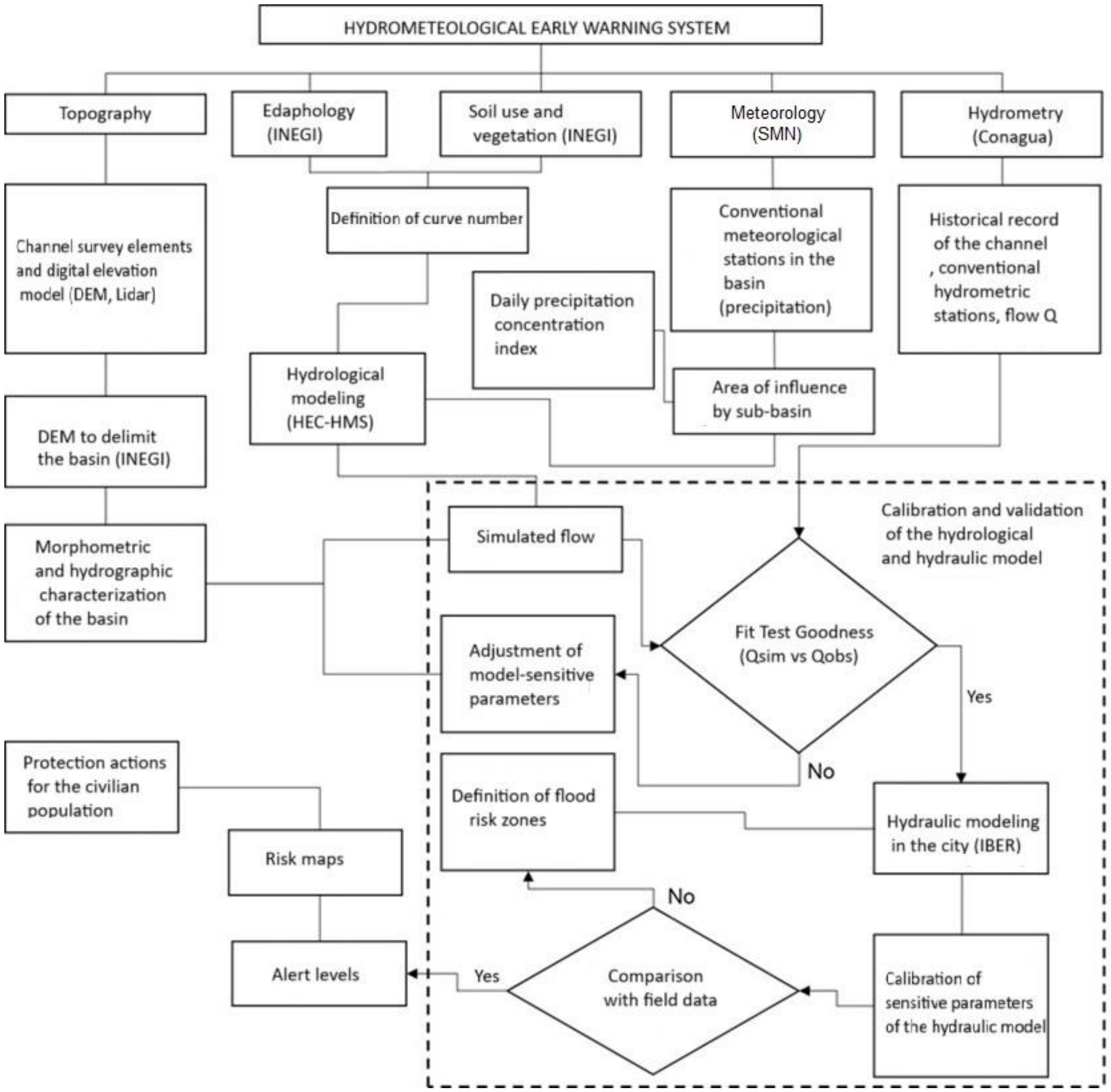

Fig. 4. Framework for FEWS implementation in the Rio Grande de Morelia basin. Source: Own design

4. Results and Discussion

A. Morphometric and Hydrographic Characterization

The morphometric and hydrographic analysis of the Rio Grande de Morelia basin involved calculating linear, area, and relief parameters. These are summarized in Table 1.

Table 1: Linear, area, and relief parameters of the Rio Grande de Morelia basin, as calculated by the authors

Characteristics	Parameters	Value
Linear parameters associated with hydrography	channel Slope	0.24%
	main channel Length	59,275 km
	Stream Order	6th order
	Fork ratio	1.91
	channels length average	0.710 km
	Drainage Density	1,622 km/km^2
	Current Density	2.03 channel/km^2
	surface flow length Average	0.308 km
Linear and area parameters of the basin	Area	1,646.299 km^2
	Form	elongated blade
	Perimeter	284.714 km
	Basin length	80,673 km
	Form Factor	0.248
	Elongation Ratio	0.56
	Roundness coefficient	3.161
Parameters associated with relief	basin slope Average	1.51%
	Mean Basin Elevation	2,176.951 m

B. Soil Characterization

The basin comprises various soil types, including Fluvisol, Gleysol, Leptosol, Luvisol, Phaeozem, Regosol, Solonchak, Umbrisol, and Vertisol. Luvisol is the predominant soil, covering 32.98% of the basin area (515 km^2), followed by Andosol, which spans 20.89% (326 km^2).

C. Land Use and Vegetation

Land use in the basin is primarily dedicated to "annual rainfed agriculture," covering 29.76% of the area (486.53 km^2). The second-largest coverage is "Pine Forest," occupying 10.61% (173.53 km^2). The urbanized areas of the basin account for 9.83% of its area (160.76 km^2).

D. Curve Number Generation for Each Sub-Basin

The Curve Number (CN) values were assigned based on the soil and vegetation characteristics in each sub-basin. The highest CN value of 81 was associated with "annual and semi-permanent irrigated agriculture" on type B soil, covering 9.4 km^2. The second largest CN area was "secondary shrubby vegetation of low deciduous forest" on type C soil, occupying 9.35 km^2 with a CN value of 78. These values were then used to calculate the weighted CN for each sub-basin, which served as input for the hydrological model.

E. Hydrological Model Calibration

The model calibration involved adjusting parameters, particularly the Curve Number (CN), to ensure alignment between simulated and observed flow data. This was achieved by fine-tuning model parameters until simulated flow closely matched observed flows within the calibration period, reducing discrepancies between the two [8]). Figure 5 presents a comparison between the simulated and measured hydrographs at The Plan hydrometric station, employing statistical tools like Calibration Coefficient (r), Schultz Criterion (D), Nash-Sutcliffe Efficiency (NSE), Mass Balance Error (m), and Root Mean Square Error (RMSE).

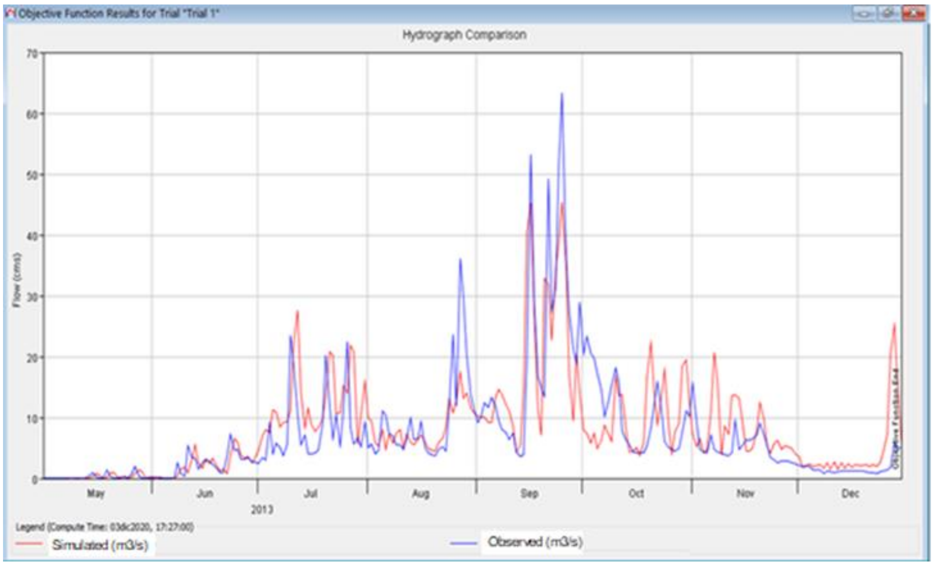

Fig. 5. Calibration hydrograph: Observed vs. Simulated flow at The Plan hydrometric station

Based on Figure 5, the difference between observed and simulated flows is 5.35 m³/s, which is considered acceptable for analysing the Rio Grande de Morelia.

F. Analysis and Identification of Vulnerable Areas from Hydraulic Modelling

The hydraulic modelling conducted for Morelia identified 878.87 hectares as high-risk flood zones (Figure 6). These areas include neighborhoods such as Fraccionamiento San Lorenzo Itzícuaro, Ampliación del Club Campestre La Huerta, Molino de Parras, Profesor Jesús Romero Flores, and the Cuauhtémoc sports unit, which align with findings reported [9]. These zones are especially susceptible to flood damage, highlighting the urgency for targeted mitigation measures and early warning capabilities.

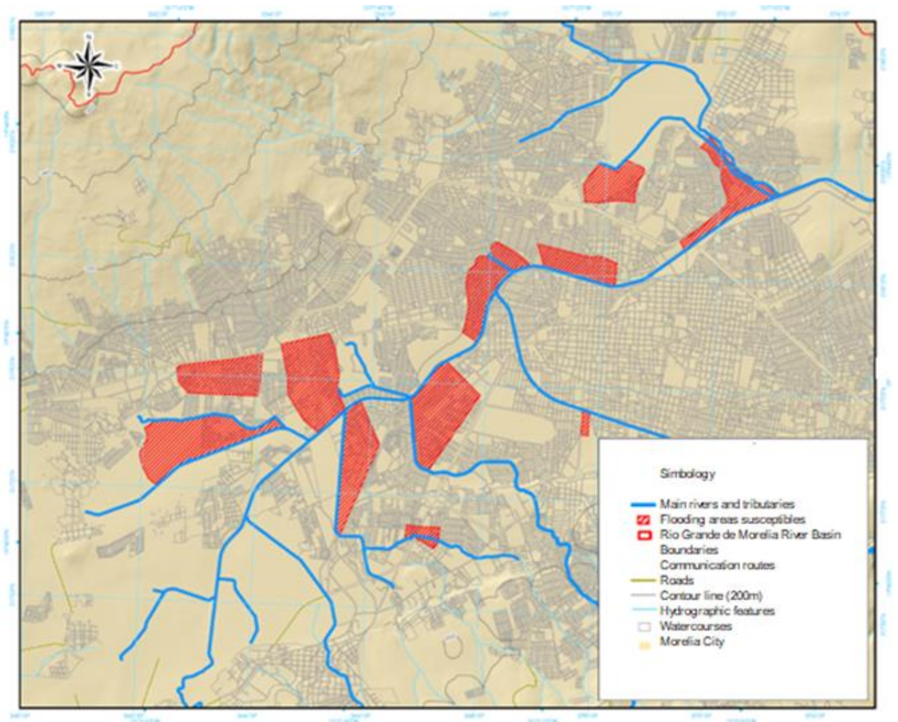

Fig. 6. Flood areas in Morelia

5. Conclusions

The implementation of a Flood Early Warning System (FEWS) in the Río Grande de Morelia basin represents a transformative advancement in proactive flood management for the area. Historically, Morelia’s response to flooding has been largely reactive, proving insufficient given the rising frequency and intensity of flood events driven by rapid urbanization and limited infrastructure planning. FEWS leverages data-driven, real-time monitoring combined with hydrological modelling to provide a structured approach for anticipating flood risks and enabling timely interventions. This approach holds the potential to save lives, protect critical infrastructure, and contribute to regional economic stability. This paper underscores the importance of high-quality, extensive precipitation and flow data and the establishment of an automated hydrometric monitoring network to enhance predictive accuracy and responsiveness. The integration of these elements within FEWS encourages collaboration among government agencies, academic institutions, private entities, and local communities, elevating flood risk management to a priority level in Morelia’s urban planning agenda.
As FEWS continues to evolve, it could become a model for flood management systems in other flood-prone regions. Ongoing improvements in data acquisition, model calibration, and community engagement can drive significant advances in flood mitigation throughout Mexico, fostering a shift toward prevention, resilience, and adaptive capacity in the face of climate variability. This system not only redefines flood preparedness but also highlights the need for a cohesive, multi-stakeholder approach to environmental resilience.

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