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Comparing the Performance of the New HEC-RAS Model Utilizing Different Modeling Techniques: A Case Study of the Tous Dam Break

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Abstract

Dams offer numerous benefits to society, but their failure can lead to catastrophic floods, causing severe damage to both people and property. Simulating dam break events and subsequent floods is essential for understanding and mitigating the risks associated with potential dam failures. In this study, three different models have been tested with the newly available HEC-RAS 6.5 model, which is freely available to the community. In this model, three models with varying dimensionality 1D, 1D/2D coupled, and 2D are tested with the test case of the Tous Dam Break. Despite the more complexity and demand in terms of computational resources, the 2D model demonstrated superior accuracy in replicating the observed flood extent and water depth. It effectively incorporated the topography and obstacles such as buildings, leading to predictions that closely mirrored the actual flood event. On the other hand, the one-dimensional (1D) and combined 1D/2D models, while they offered a decent portrayal of how the flood unfolded, consistently fell short in accurately estimating how far the floodwaters would spread, especially within the intricacies of floodplain environments. This consistent underestimation highlights the crucial necessity of selecting an appropriate modeling technique that aligns with the geographical intricacies and the desired granularity of detail.

Subject Areas

Hydrology

Keywords

HEC-RAS, Tous Dam, Dam Break Case, Hydraulic Modeling

1. Introduction

Flooding from dam failures, excessive rainfall, and storm surges poses a serious threat, potentially leading to major disasters and significant economic losses. Additionally, climate change increases the likelihood of more frequent and severe flooding and river inundation [1] [2]. It has been possible to simulate extreme events using a variety of methods [3] and models of varying complexity, ranging from simple cross sections of a plane representing the water surface to a full three-dimensional Navier-Stokes equation solution based on digital elevation models.

The shallow water flows have been simulated using hydraulic models of varying dimensionality, e.g. one-dimensional (1D) [4], two-dimensional (2D) [5] and coupled (1D/2D) [6]. Globally, one-dimensional finite difference solutions to the full Saint Venant equations have been used to determine these flood inundations. It involves modeling river channels and floodplains together by using geometry taken perpendicular to the flow direction. Due to easy use and efficiency, floods are generally modeled using a one-dimensional approach (e.g. BASEMENT, HEC-RAS, MIKE 11, etc.) as 1D models are easy to use and construct because they require less data.

The most widely used method around the world to determine these flood inundations has been one-dimensional finite difference solutions of the full Saint Venant equations. In such types of schemes, main channel rivers and floodplains are expressed in a series of cross sections perpendicular to the flow direction, which are modeled together. Due to easy use and efficiency, floods are generally modeled using a one-dimensional approach (e.g. BASEMENT, HEC-RAS, MIKE 11, etc.). Surely 1D models are easy to use and build, but the results of such models have significant inaccuracies in the floodplains [7] [8]. Even if these models are of moderate complexity, their (one-dimensional) schemes failed to describe the floodplain inundations and (sometimes) flows in the main channel.

In contrast to this, 2D models are very complex to build and require much greater simulation time, but the results are more accurate. Two-dimensional (2D) flood modeling can provide abundant information about the flood wave propagation and dynamics of flooding, which can be used to improve flood management. However, high-resolution terrain data are often required to justify 2D flood inundation modeling, which is increasingly available in the form of digital elevation models (DEMs) and digital terrain models (DTMs) obtained through remote sensing methods. The performance of flood inundation models can be studied with reference to their stability, accuracy, and computational efficiency, resulting in long-run times, which are unfeasible for many problems. So many methods have been used to solve this type of problem like using faster hardware [9], using coarser meshes [10] and parallelizing the source code with OpenMP [11] and GPU technology [12] using a simplified form of governing equations, e.g. diffusion wave.

A relatively new approach is the 1D/2D coupled approach. In this integrated approach, the 1D and 2D models are linked to each other and dynamically represent the river and floodplain interactions [6] [13]. A one-dimensional (1D) model solves the hydraulics equations in the river channel network, described with cross sections and all the important structures. The results of the simulation at each time step obtained from the one-dimensional scheme are used as internal boundary conditions for the two-dimensional scheme, which is used to simulate the inundation over the floodplain [14] [15].

1.1. Tous Dam and Sumacarcel Town

The Tous Dam, situated in the central part of the Mediterranean coast of Spain near Cartagena, drains the Jucar River basin with a catchment area of 17,820 km^2 (**Figure 1**). The catchment has a typical Mediterranean climate characterized by frequent heavy downpours resulting from high solar radiation and warm sea waters. Between October 20 and 21, 1982, an intense rainfall event occurred in the hinterland of the central Mediterranean coast of Spain, caused by a cold, high-altitude depression interacting with the surrounding warm, humid air. The Jucar River basin, which was significantly affected by the rainfall, received 500 mm in 24 h, which led to widespread flooding. On 20 October, at about 1900 hours, the Tous Dam collapsed with devastating effects on the downstream riparian areas. More description of the Tous Dam break can be on [16].

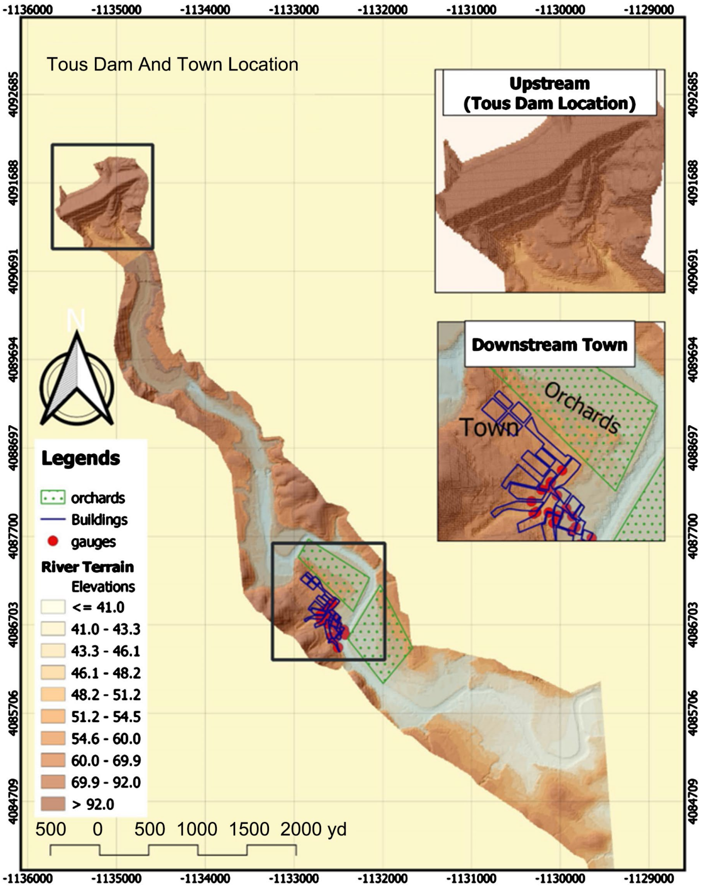

Figure 1. Location of Jucar River, Tous Dam and Town Sumarceal.

A total rainfall volume of almost 600 × 10^6 m^3 fell over the basin, largely exceeding the capacity of the old Tous reservoir (120 × 10^6 m^3), estimated to have received a flood peak of 9900 m^3/s. All through this time, the water level in the reservoir continued to increase till it attained the crest elevation of the dam (98.5 m) at about 1730 hours and 15 min later started spilling over, thus initiating the dam erosion. It can be seen that the water level never exceeded the MSL (99.5 m) of the dam and collapsed at about 1915 hours with elevation dropping to 81 m at 2330 hours.

The dam break wave wreaked havoc as it propagated downstream, affecting many towns and villages having a combined population of almost 200 thousand people and causing 8 fatalities. The major devastation occurred in the town of Sumacárcel, which was located at the toe of the right bank of the river on a hill about 5 km downstream of the Tous Dam. Although the terrain has steep slopes due to the mountainous region, which protected the buildings from flooding, however, the older part of the town located closer to the riverbank was massively flooded with water depths varying from 6 m to 7 m witnessed there.

1.2. Hydraulic Modeling Tool

HEC-RAS is one of the most popular flood modeling software programs. This model can perform 1D and 2D unsteady flow simulations, as are sediment transport and water temperature/quality simulations. In this model, natural and constructed river channels are represented geometrically and hydraulically computed. Although HEC-RAS can perform a wide variety of functions, the focus of this paper will be on its ability to run both 1D flows of water, 2D floods, and combined 1D/2D, particularly the analysis of floods caused by dam or levee breaches [17].

One-dimensional river hydraulic modeling operates under the assumption that water flows longitudinally. These models use sequential terrain cross-sections to simulate water flow, facilitating the calculation of parameters like flow velocity and depth. In each cross-section used by HEC-RAS, the software assumes that the water surface is horizontal and perpendicular to the direction of flow. This assumption allows for the omission of momentum exchange between the floodplain and the channel.

Two-dimensional flood models excel at managing complex and irregular topographies by capturing water movement in both longitudinal and lateral directions, while typically ignoring vertical velocity components. These models represent terrain as a continuous surface and use a mesh or grid system to facilitate calculations. HEC-RAS, for example, employs a sub-grid algorithm that combines a coarse computational grid with detailed topographical information to improve accuracy. Depending on the specific needs of the simulation, either the full Saint-Venant equations or the diffusion wave equations may be used. The full Saint-Venant equations provide a comprehensive but computationally demanding description of unsteady flow, whereas the diffusion wave equations offer a quicker and more stable solution. HEC-RAS 2D model applies shallow water equations to describe water motion in terms of depth-averaged two-dimensional velocities and water depth, considering the effects of gravity and friction. The finite-volume method utilized in HEC-RAS is advantageous due to its conservativeness, geometric flexibility, and conceptual simplicity, making it a robust choice for hydraulic modeling [18].

In the latest version of HEC-RAS, a new feature has been introduced that allows for combined 1D and 2D unsteady-flow routing within the unsteady-flow model. This enhancement facilitates the analysis of larger river systems, applying 2D modeling specifically in areas where greater hydrodynamic accuracy is necessary. The integrated 1D and 2D solution algorithm provides continuous feedback between the two flow elements at each computational step. This capability ensures more precise measurements of headwater and tailwater levels, flow rates, and any submergence at hydraulic structures, following the approach detailed by Brunner, on a time-step-by-step basis.

2. Materials and Methods

The model simulations were conducted in three distinct phases: one-dimensional (1D) modeling, two-dimensional (2D) modeling, and coupled one-dimensional/two-dimensional (1D/2D) modeling using the HEC-RAS 6.5 software. Each phase utilized a digital terrain model (DTM) created by CEDEX, based on 1998 cartographic data, which included the Tous Dam as it was already constructed and operational at that time. Although two DTMs were available, one from 1982 and another from 1998, the 1998 DTM was chosen due to its superior quality and greater level of detail. After running the simulation, the resulting flood data flood extent and water depth were mapped using the geographic information system (GIS) tool, and then compared to the flood results from the observed data. In this way, the model's capability and accuracy can be assessed.

2.1. Setup for HEC-RAS Model

One-dimensional (1D) cross-sections were meticulously created through the manual digitization of various thematic vector layers, such as river networks, stream centerlines, riverbanks, and flow paths. These were based on a digital elevation model (DEM) crafted in 1998, featuring a spatial resolution of 5 meters. Additionally, an attribute table for each cross-section was developed. The design of these cross-sections was governed by strict hydrological protocols, ensuring they spanned from the left to the right bank, were perpendicular to the thalweg, and avoided any intersections among them. The distance between cross-sections ranged from 50 meters to 150 meters. Subsequently, these cross-sections were fed into the HEC-RAS software to execute one-dimensional flood simulations. Manning's roughness coefficients were set at 0.03 for the river's main channel and 0.1 for the orchard areas. The simulation utilized the outflow hydrograph from the Tous Dam as the inflow data. For the advanced 1D/2D coupled simulation, the main channel was modeled with the established 1D cross-sections, while the urban layout of Sumarceal was delineated using 2D cells of 5 m × 5 m, capturing every building within the township. All other simulation inputs, including Manning's roughness coefficients, slope, and boundary conditions, remained consistent with the 1D model. In the exclusive 2D modeling process, a structured square mesh with a resolution of 5 meters was employed to discretize the area, encompassing all physical features such as buildings and orchards, ensuring a comprehensive representation of the simulation. All the geometric data created for the three simulations is shown in **Figure 2**.

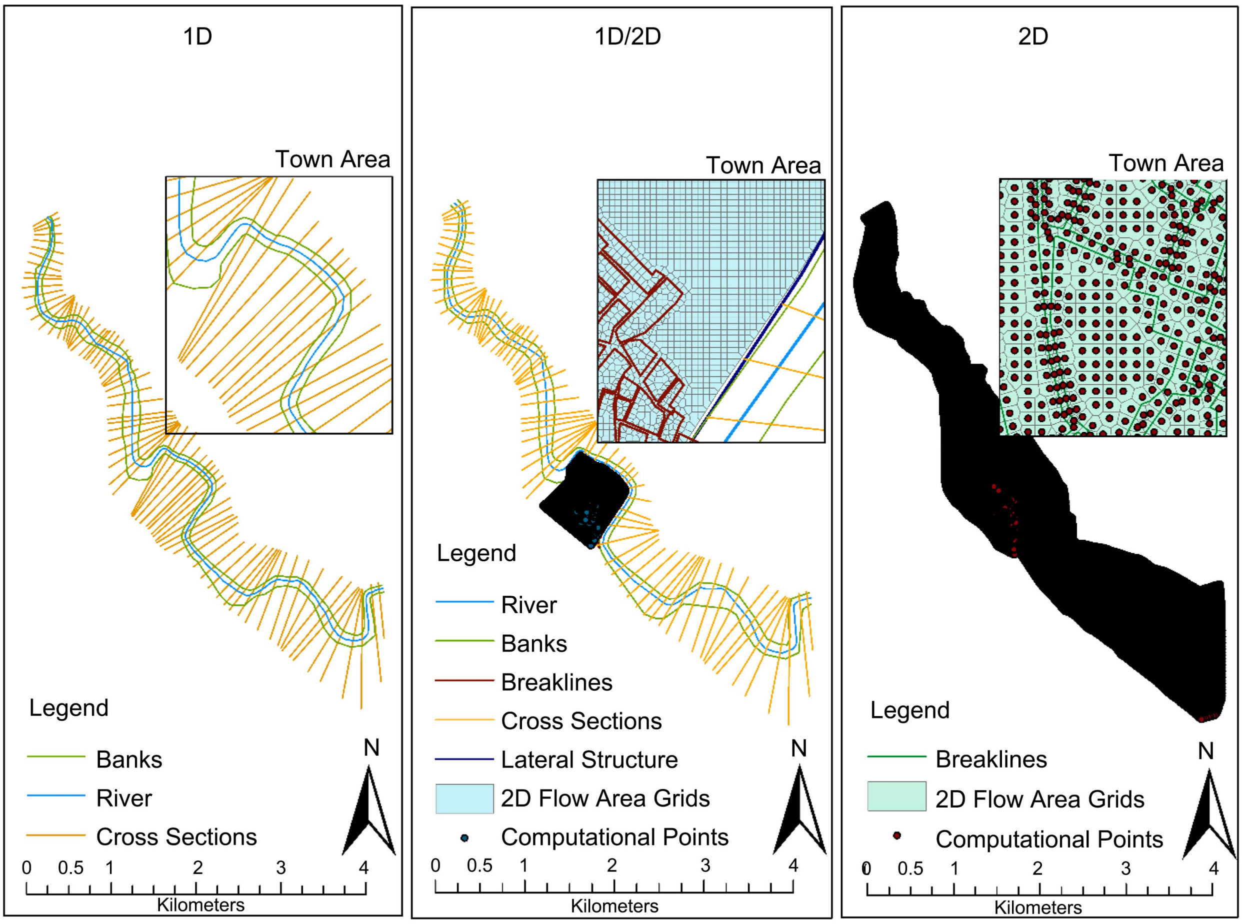

Figure 2. Geometric files generated in HEC-RAS for 1D, 1D/2D and 2D models.

2.2. Data for Building the Numerical Model

An estimated 100 mm rainfall fell till 800 h on 20 October, resulting in the runoff before the dam spillover; another about 100 mm rain fell during the remaining part of October 20 and 21, resulting in the huge flow volume arriving at the dam site. The Tous Dam break was caused by a breach that developed progressively. The most important parameter that determines the severity of flooding in the downstream regions is the breach outflow, which is used as inflow hydrograph (**Figure 3**) for the model. However, in the absence of actual flow measurements, the CEDEX (Centre for Studies and Experimentation of the Ministry of Public

Works, Spain) developed a most likely outflow hydrograph by combining observations, hydrologic simulation, and results of the physical model at a scale of 1:50. This hydrograph was used as the upstream boundary condition.

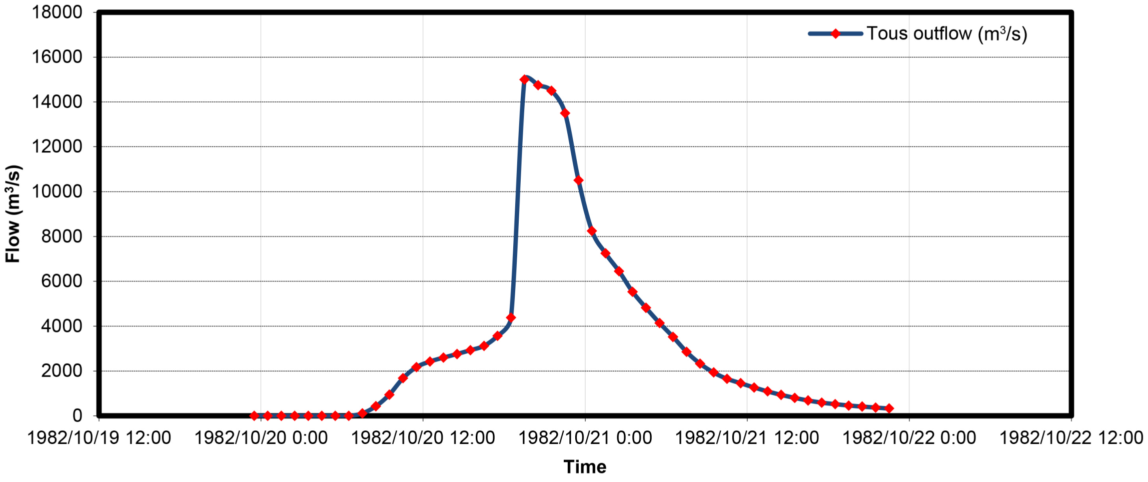

Figure 3. Inflow hydrograph.

2.3. Boundary and Initial Conditions

The river reach under analysis extends approximately 1 km downstream from Sumacárcel in the digital terrain model (DTM). Although there are no direct observations of the flow regime in the main channel during the dam break wave, simulations indicate that the flow remained subcritical. Consequently, it is reasonable to assume a free outflow or critical flow condition at the downstream boundary. The influence of the downstream boundary condition on numerical results is significant primarily when the boundary is close to the area of interest. Since the downstream boundary in the Tous Dam case is located more than 1 km from Sumacárcel, a zero gradient or free outflow condition is applied at this boundary. There is also limited data on the initial water depth in the Jucar River. The river's typical flow of approximately 50 cubic meters per second is negligible compared to the peak flood flow from the dam breach. Moreover, as the spillway gates of the Tous Dam were closed at the time of the breach, the river flow consisted solely of the base flow and any surface runoff from the surrounding basin. Therefore, for initial calculations, it is reasonable to assume that the riverbed was dry.

It is important to note that the town's terrain is entirely paved with concrete, which eliminates any risk of erosion during the flood. Consequently, there are no concerns regarding changes in topography due to sediment movement within the town. The CEDEX survey provides a comprehensive list of gauge locations along with the maximum water depths recorded at each point. Figure 1 displays the placement of these 21 gauging points on the digital terrain model (DTM). Notably, several gauges, specifically 5, 9, 15, 17, 18, and 21, reported minimal or no flooding, indicating areas that experienced little to no floodwater (Table 1). These points effectively delineate the flood's boundary within the town, serving as essential benchmarks for validating the results of mathematical flood models.

Table 1. Estimated maximum water depth at different gauges.

Gauge	Estimated Maximum Water Depth	Comments
1	17.5 - 19	Riverbed at bridge
2	8.0 - 9.0	Cinema
3	7.0 - 8.0	Church Street
4	7	Condes de Orgaz St.
5	0.2	Júcar Street
6	5.0 - 6.0	Proyecto C Street
7	6	Old City Hall (Rough)
8	5	Pendulum Clock House
9	0	Era Square
10	4	Júcar Street
11	2	Stairs Street
12	5.0 - 6.0	Condes de Orgaz St.
13	2.5 - 3.0	Valencia Street
14	2	Pintor Sorolla Street
15	0	Valencia Street
16	3.0 - 4.0	Pintor Sorolla Street
17	0	Pallecer Street
18	0	Severo Ochoa Street
19	2.0 - 3.0	Virgen Street
20	2	Virgen Street
21	0	West Avenue

2.4. Roughness Coefficient

The variation in soil types, vegetation, and crop fields along the river reach results in significantly different friction levels across the area. While using a uniform base Manning coefficient for the entire reach is a straightforward approach, it may overlook critical flow characteristics. Aerial photographs can help identify agricultural land and variations in vegetation, but detailed roughness distribution data does not always improve the accuracy of flood simulations compared to observed results. In Sumacárcel, the presence of orange tree orchards surrounding the town had a significant impact on flood dynamics by increasing flow resistance and effectively impeding the floodwaters. Eyewitness accounts suggest that the floodwaters initially moved toward the opposite riverbank due to the natural topography. However, this bank, densely populated with tall orange trees (5 - 6 meters in height), acted as a barrier, causing the floodwaters to redirect laterally into Sumacárcel.

For this study, a base Manning roughness coefficient of 0.030 was applied to the entire river reach, except in the orange tree orchards, where a higher coefficient of 0.1 was used, based on their density as identified in aerial photographs.

3. Results and Discussions

Figure 4 presents a comparative analysis of water depths obtained from one-dimensional (1D), two-dimensional (2D), and coupled 1D/2D hydraulic models against observed measurements from 21 flood gauge sites. The observed data were collected through a post-flood survey where flood marks were meticulously noted. Notably, the results demonstrate that the 2D modeling approach outperforms its counterparts. For instance, at Gauge 1, located within the main channel, the observed water depth peaked at 19 meters, a figure that the 1D model did not capture, estimating a depth of only 16 meters. This underestimation may be attributed to the 1D model's inability to factor in the obstructive influences of buildings along the channel. The performance of the 1D/2D coupled model was also underwhelming; contrary to expectations, it estimated the depth at Gauge 1 to be 15.63 meters, which did not align closely with the observed reality. On the other hand, the 2D simulation excelled, estimating a maximum water depth of 18.4 meters at Gauge 1, closely matching the actual observation. This accuracy highlights the 2D model's robustness, as it accounts for various impediments and critical geographical features, offering a nuanced simulation of the flood dynamics.

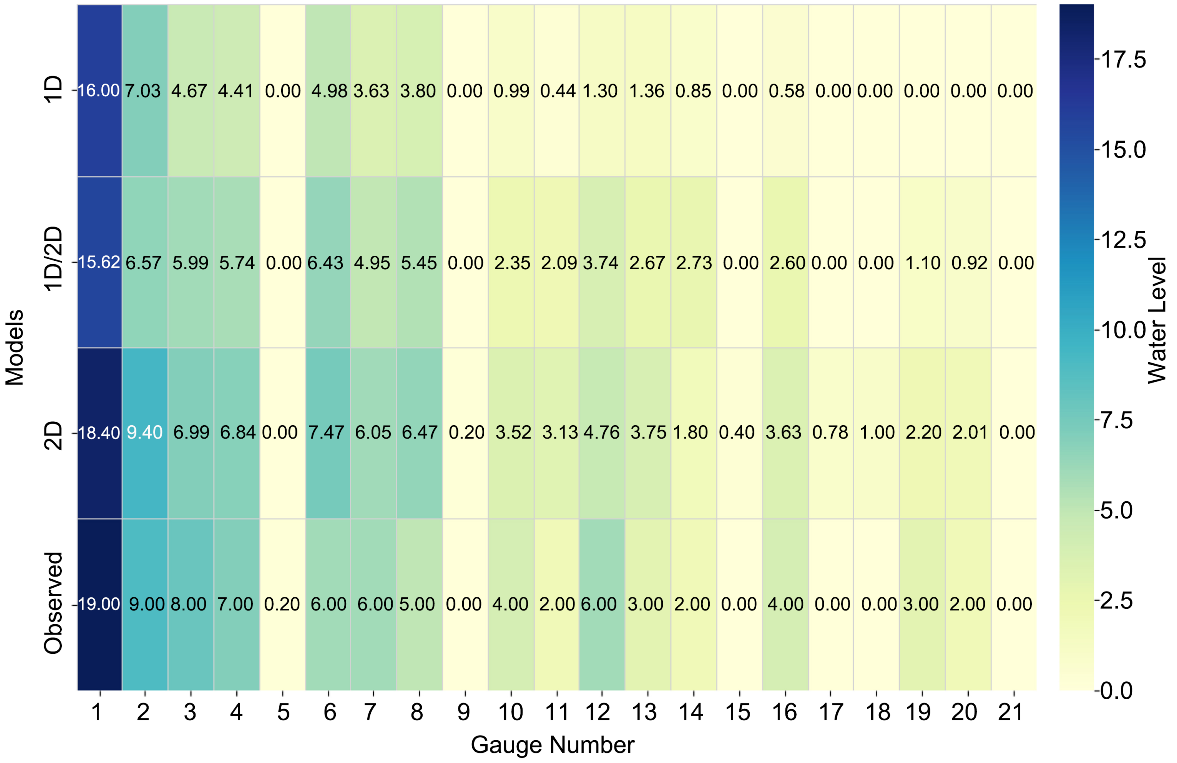

Figure 4. Water depth elevation comparison of 1D, 1D/2D, 2D model and observed data.

Figure 1 delineates the positioning of gauge points in the flood-impacted zone, with Gauge 1 situated directly in the main channel of the Jucar River, while the remaining gauges are distributed throughout the town area. The progression of water depth over time at Gauges 1, 7, and 8 is depicted in the figure. As illustrated in Figure 5, Gauge 1 experiences a rapid increase in maximum water depth as the flood wave arrives, followed by a gradual decline, which mirrors the expected behavior in a realistic flood event. At Gauge 1, within the main river channel, the 2D model shows a peak water depth occurring at 20:09 h, reaching 18.59 m. The 1D model's peak, at 20:15 h, reaches 15.98 m, and the 1D/2D model's peak, at 20:10 h, hits 15.59 m. Compared to the other models, the 2D model aligns more closely with the observed data, effectively capturing the flow depth's peak. The 1D and 1D/2D models, while accurately reflecting the timing of the water depth evolution, tend to underestimate the depth compared to observed values. Similarly, for Gauges 7 and 8, the 2D model most accurately predicts the observed peak water depths. The 1D and 1D/2D models, however, fall short in their estimations, consistently providing lower depth values than those observed.

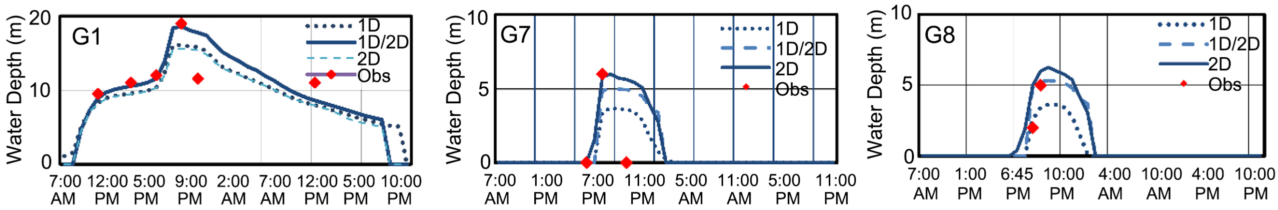

Figure 5. Comparison of water depths at G1, G7, and G8 of different models with observed.

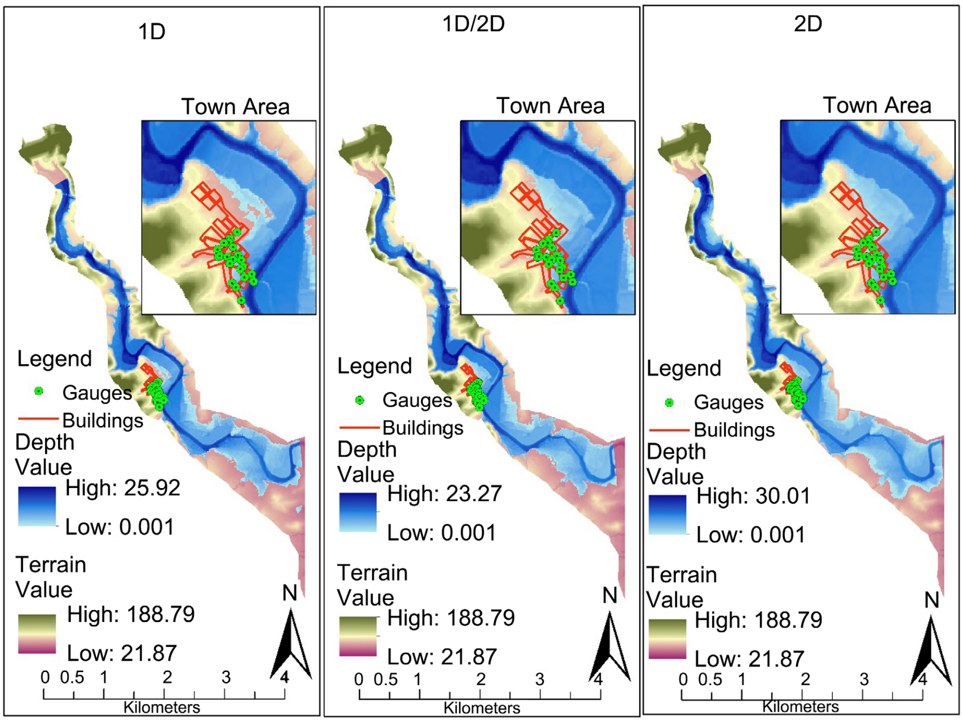

Figure 6. Extent of water depth of 1D, 1D/2D and 2D models.

Figure 6 displays the inundation extents as depicted by water depth elevations from one-dimensional (1D), coupled one-dimensional/two-dimensional (1D/2D), and two-dimensional (2D) simulations. Generally, the flood coverage projected by the HEC-RAS simulations corresponds closely with the results of the other models and the actual flood data collected from field surveys. The models are consistent with the established local topography, indicating their overall reliability. Despite this agreement, the 1D and 1D/2D simulations were noted to underestimate the flood's reach when compared to the empirical survey data, suggesting a limitation in capturing the full scope of the inundation. Conversely, the 2D HEC-RAS model not only aligns well with the observed inundation, but also slightly overestimates the maximum flood extent, reflecting a more extensive coverage than what was recorded in the surveys for both itself and the other two modeling approaches.

4. Conclusion

The comprehensive comparison of one-dimensional (1D), coupled 1D/2D, and two-dimensional (2D) hydraulic models has highlighted the strengths and limitations of each approach in simulating flood inundation from dam breaks. Through the case study of the Tous Dam failure and the consequent flooding of the Jucar River basin, the model's performance was evaluated against observed data collected from strategic gauge points. The 2D model, despite being more complex and demanding in terms of computational resources, demonstrated superior accuracy in replicating the observed flood extent and water depth. It effectively incorporated the topography and obstacles such as buildings, leading to predictions that closely mirrored the actual flood event. The 1D and 1D/2D models, while providing reasonable approximations of the flood progression, tended to underestimate the extent of inundation, particularly in complex floodplain areas. This underestimation emphasizes the need for a careful selection of the modeling approach based on the terrain and the level of detail required. The successful application of these models, particularly the 2D approach, underscores the importance of high-resolution topographical data and the benefits of advanced computational techniques, including the use of GPUs and optimized algorithms, to manage computational demands. The findings of this study advocate for the use of detailed 2D modeling as a robust tool in flood risk management and emergency planning, especially in light of the increasing flood risks posed by climate-impacted extreme events and the need for timely and accurate flood forecasting. Overall, the study contributes valuable insights into the capabilities of hydraulic modeling tools and lays the groundwork for future improvements in flood simulation accuracy, potentially aiding in the reduction of property damage and loss of life during flood events.

Data Availability

Data is available on the following link:
https://doi.org/10.1080/00221686.2007.9521832.

Conflicts of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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