# Comparison Between HEC-RAS and TELEMAC-2D Hydrodynamic Models of the Loire River, Integrating Levee Breaches

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# Comparison between HEC-RAS and TELEMAC-2D hydrodynamic models of the Loire River, integrating levee breaches

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## KEY WORDS

Hydrodynamic model, HEC-RAS, TELEMAC-2D, Loire river, Levee breaches, Flood risk.

## ABSTRACT

*Throughout history and in the present era, flooding has represented a significant challenge, resulting in substantial property damage and a noteworthy loss of lives, despite extensive risk mitigation measures and billions invested in flood defenses globally. The Loire river, the longest in France, has a rich history of flooding. To mitigate floods, levees have been built since the Middle Ages. For this study, a 2D hydraulic model was built using HEC-RAS, covering a 50-kilometer strech of the river from Gien to Jargeau. Building upon a previously developed numerical model of the study area by IRSN using TELEMAC-2D, the HEC-RAS model was created based on its data and assumptions. The objective was to assess the performance of both software by comparing the obtained results. The HEC-RAS numerical model has been calibrated for the largest recorded flood event, which occurred in 2003, and validated on two other major floods. This allowed us to estimate the impacts of flooding, with a particular focus on the simulation of an estimated 1000-year return period flood and incorporating the analysis of multiple levee breach scenarios. Furthermore, the results obtained with the hydrodynamic models implemented using HEC-RAS and the existing TELEMAC-2D model were summarized, encompassing their performance, capabilities, limitations, and the analysis of levee breaches scenarios testing various breach parameters. This analysis provides a robust set of criteria to guide to selection of the most suitable tool for further studies based on the objectives of each project.*

## 1. INTRODUCTION

The Loire river holds a position of utmost importance in France as the country's longest river, with a basin that drains a sizable region of 117,000 km$^2$ in central France [1]. Additionally, the Middle-Loire is safeguarded by embankments that date back to the 11th century, indicating that flood protection has historically been a primary concern [2]. The Loire river features many levees along its course, covering approximately 70 km in the study area.

The study area of this analysis is located between Gien and Jargeau (Figure 1). This model covers a total land area of 325.2 km$^2$ , representing a river section of around 50 km and includes the Dampierre Nuclear Power Plant (CNPE Dampierre) located on the right bank of the river, approximately 10 km downstream of Gien.

In a previous study phase, a 2D hydrodynamic numerical model of the study area was created using TELEMAC-2D. in this phase, a 2D hydrodynamic model has been constructed using HEC-RAS, including calibration and validation for both historical and projected flood events. The same data and criteria have been considered for the creation of both models, to enable the comparison of the software's performance on flood dynamics and results.

Additionally, the 19th century saw the most recent historical breaches on the Loire [4], where the majority of the breaches appear to have happened when the levees were submerged [5]. In this regard, levee performance has been analyzed at four points along the river stretch in order to assess the potential consequences of levee breaches on the floodplain and to estimate water levels.

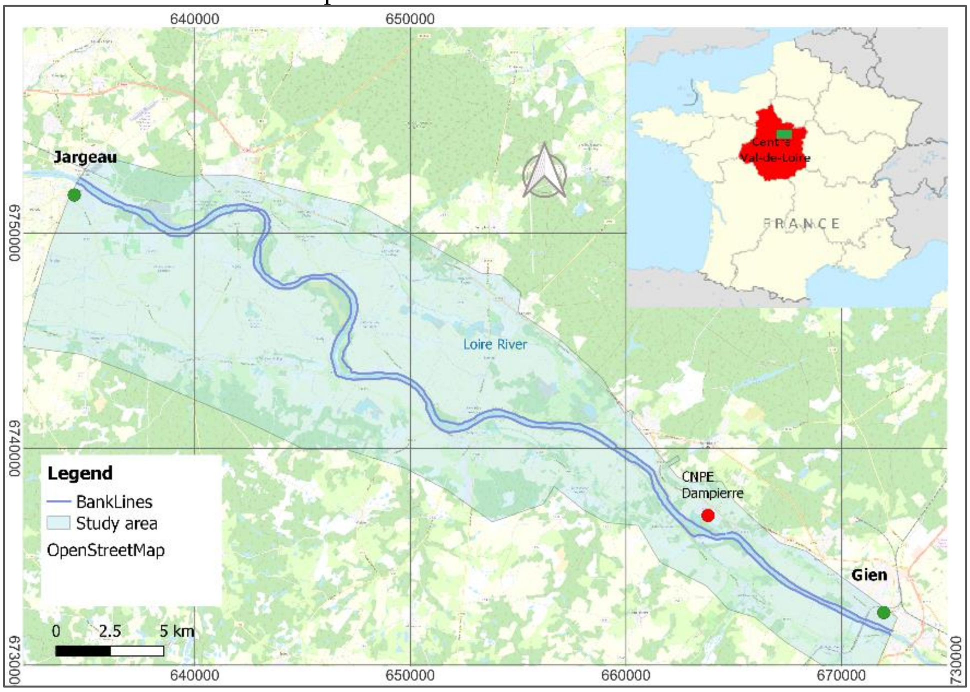


**Figure 1**: Study area: Loire river between Gien and Jargeau, located in Centre-Val de Loire, France (source : openstreetMap).

This study is centered around developing a 2-D hydrodynamic model using HEC-RAS, with a primary focus on evaluating and comparing the performance of two distinct softwares (HEC-RAS 2D and TELEMAC-2D), in the context of a real-life flood study. It aims to establish a robust set of criteria to guide the selection of appropriate tools based on specific requirements.

## 2. MATERIALS AND METHODS

### 2.1. Data

The required data for this model encompassed water levels and flow rates recorded at the Gien station spanning from 1952 to 2019, sourced from the Hydroportail database. Additionally, water level data from multiple river stations during significant flood events from 1973 to 2016 were acquired through the Direction Régionale de l'Environnement, de l'Aménagement et du Logement Centre-Val de Loire (DREAL CVL). Furthermore, DREAL CVL provided a Digital Elevation Model (DEM) with a 1-meter resolution for the study area, acquired in 2002, as well as cross-sectional riverbed data, consisting of two sets: one collected prior to the year 2000 and the other one after 2000.

### 2.2. HEC-RAS: 2D hydrodynamic model

The representation of integrating topography data into the HEC-RAS model was initiated with the generation of the Digital Elevation Model (DEM) of the riverbed. This specialized DEM was constructed using a selection of 73 river cross sections. Subsequently, the riverbed DEM was seamlessly incorporated into the broader DEM encompassing the entire area.

When creating the mesh, primary considerations revolve around ensuring an accurate representation of reality, as the mesh size notably influences the model's definition. The mesh size is determined through a careful equilibrium between computational time, stability concerns, and model precision [6]. This mesh size comprises two distinct dimensions: 60 meters for the broader region and 20 meters for the refined area that includes the riverbed and sensitive floodplains. Additionally, the break-lines feature was employed to accurately define regions of hydraulic interest, such as levees, riverbeds, channels, and others.

Open and closed boundary conditions were set for the model's computational domain definition: upstream and downstream areas represent water inflow and outflow with open boundary conditions, while the rest of the perimeter featured closed boundary conditions. For the upstream boundary condition, hydrographs were based on significant recorded historical flood events in 2001, 2003 and 2008, along with a computed hydrograph for an extreme 1000-year return period flood event. For the downstream boundary condition, a rating curve based on the Manning-Strickler equation projected flow for historical and projected flood events, taking the topography into account was set up.

To account for the continuous flow of the Loire river, and initiating the hydraulic model, two start-up files were created to capture the initial conditions for each event. The first file was used for the 2003 flood event, as well as for the 2008 event and the projected 1000-year flood at 425 $m^3/s$. The second file applied to the 2001 event, with flow rates ranging from 0 $m^3/s$ to 769 $m^3/s$ over a 12-hour ramp-up period. Both files were simulated for five days, resulting in stable river flow after a simulated period of 48 hours.

### *2.2.1. Calibration*

For calibrating the hydrodynamic model, the hydrograph from the December 2003 flood event was used. This event holds significance as the major flood event recorded with an estimated return period of around 50 years, featuring a peak flow of 3310 $m^3/s$. Leveraging data from various hydrometric stations, the calibration process for the 2003 flood event was conducted through manual adjustments. The setup of the land cover layer involved altering the Manning coefficient of the riverbed from downstream to upstream. This calibration process was executed iteratively until water levels at specific points fell within a tolerance range of ± 0.25 m. The analysis involved assessing the water levels at 21 predefined points along the Loire.

### *2.2.2. Validation*

The model was validated using recorded water levels from the May 2001 and November 2008 flood events, with return periods of 5 to 10 years and maximum flows of 2400 $m^3/s$ and 2320 $m^3/s$ respectively. Validation involved 26 points along the river. For the 2001 flood event, most differences of water levels values were within 0.25 m of the historical measurements, except 5 points with a maximum difference of 0.38 m. Validation of the 2008 flood event generally fell within the assumed 0.25 m tolerance, though 11 values exceeded it, with a maximum difference of 0.47 m.

### *2.2.3. Sensitivity Analysis*

Throughout the modeling process, it became evident that the choice of parameters, such as mesh size, equation selection, and time step, holds substantial influence over the simulation outcomes. Consequently, sensitivity analyses for these factors were conducted, with one parameter varied at a time. This approche allowed for a comparative assessment of maximum water depth under different scenarios.

- Mesh-size

Two different regular mesh configurations were tested in the broader area. Mesh 1, comprised two distinct dimensions of cell size: 60 m x 60 m for the broader area and 20 m x 20 m for the refined area encompassing the riverbed and sensitive floodplains. Mesh 2, had dimensions of 40 m x 40 m for the broader area and 20 m x 20 m for the refined area. The results revealed an average difference of water levels among the 21 defined control points of one centimeter, within a range of 0 to 0.03 m. Notably, the first mesh was simulated 1.2 times faster in terms of computational time and was selected for this study.

- Equations

The HEC-RAS code was executed to solve both the Shallow Water Equations (SWE) system and the Diffusion Wave Equation (DWE) for this model. The resultats showed variations in water levels at the 21 calibration points, with an averaging difference of 0.17 m between the SWE or DWE solutions. The maximum recorded difference was 0.32 m, while the minimum was 0.06 m. Notably, the SWE simulation exhibited higher water levels due to reduced water dispersion on the floodplains. However, the discrepancies in floodplains observed were minimal.

- Time-step

The model underwent testing using time steps of 2, 5, 10, and 30 seconds. This testing demonstrated stability, but it also led to longer simulation times for the shorter time steps. As the time step varied from 2 to 30 seconds, noticeable water level differences emerged. On average, these differences were around 0.036 m across the 21 calibration points due to the time step variation. The largest observed difference was 0.11 m, while the smallest was 0.02 m. Notably, this adjustment also resulted in a simulation time that was up to 11.7 times faster.

### *2.2.4. Levee breaches*

Levee breaching can be described as the loss of integrity or significant geometric alteration of the flood protection structures [3]. Four levees were chosen based on historical data as the most probable for breaching, shown in Figure 2, with overflow being identified as the most likely failure mode. For the study of the Loire river between Gien and Jargeau, a total of 16 cases were analyzed [4]. Four keys parameters were modified: overflow level, breach depth, breach duration, and breach length as detailed in Table 1. Each parameter underwent testing across four distinct scenarios, with one parameter being altered at a time. The other three are set to common values (S = 0.1 m, L = 200 m, P = 75%, and T = 0).

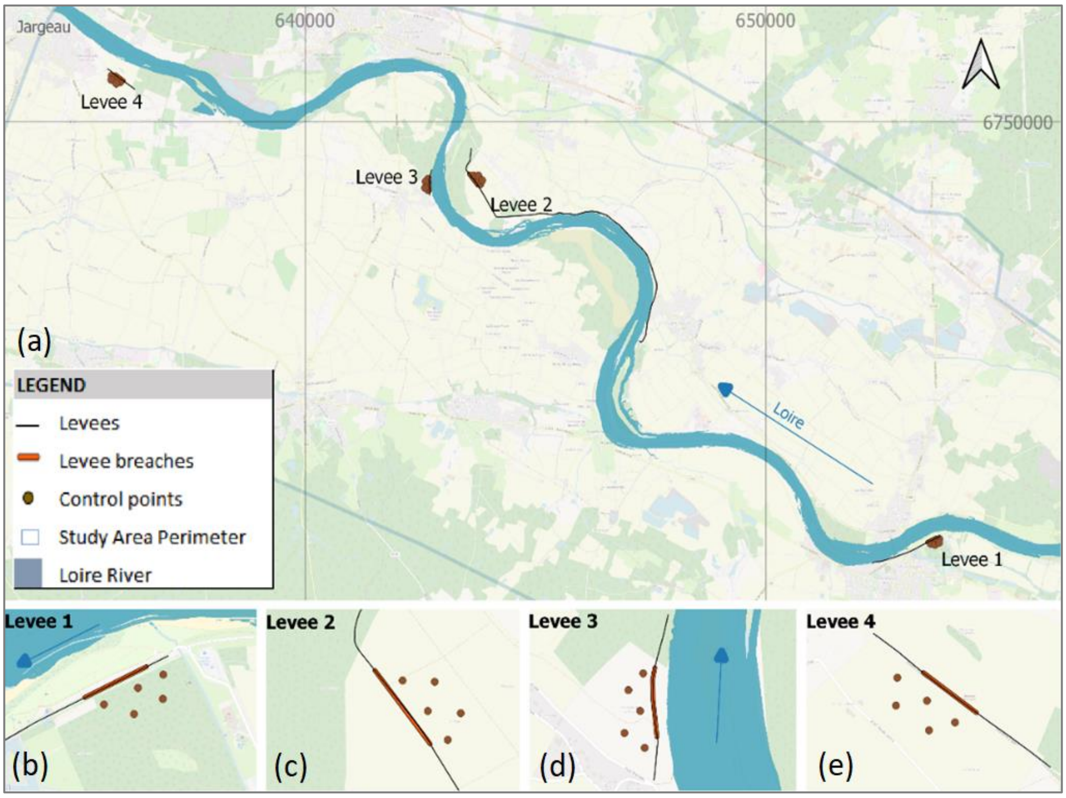


**Figure 2**: Location of the selected levees to breach in the study area (a), along with strategically placed control points behind each levee (b, c, d, e) for breaching analysis.

**Table 1**: Levee Breaches, 16 study cases altering one parameter at each simulation

| **Levee Breaches - 16 Cases** | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Overflow (m)** | | | | Depth of the breach (%) | | | | Duration of the breach (h) | | | | Length of the breach (m) | | | |
| C 1 | C 2 | C 3 | C 4 | C 5 | C 6 | C 7 | C 8 | C 9 | C 10 | C 11 | C 12 | C 13 | C 14 | C 15 | C 16 |
| 0.05 | 0.10 | 0.15 | 0.20 | 25 | 50 | 75 | 100 | 0 | 6 | 12 | 18 | 100 | 150 | 200 | 250 |

### **2.3. TELEMAC-2D: Hydrodynamic model**

The TELEMAC-2D model characterizes the Loire river stretch between Gien and Jargeau. It initially underwent development by the IRSN in 2019 and received further enhancements in 2021, including a detailed analysis of levee breaches. The model features various key attributes. The mesh size varies, with dimensions ranging from 40 m in the refined area to 60 m in the rmainder of the study area. During the calibration process, the hydrograph of the 2003 flood event, which reached a peak of 3310 $m^3$/s, was employed. For validation, the model was simulated using hydrographs from the 2001 and 2008 flood events. A land use map covering 9 areas, with 8 zones corresponding to the riverbed, was integrated. Each zone was assigned a distinct Strickler coefficient. The Strickler coefficient of the riverbed areas was adjusted during calibration to match water level differences within a tolerance range of ±0.25 m [7]. Finally, levee breaching were analyzed for four parameters (final length, final depth, opening duration, and breach overflow control level) to assess the individual impact of each parameter.

# 3. RESULTS

## 3.1. HEC-RAS

The simulation results focuses on three critical aspects: floodplains, water depth, and velocities.

### *3.1.1. Floodplains*

Flood events occurring in the years 2001, 2003, and 2008, characterized by return periods ranging from 5 to 50 years, have been examined in this study. During these events, the flooded areas were indeed analyzed, as insights into levee effectiveness were provided, as water was mainly contained behind these barriers. Furthermore, the simulation of the extreme event with a 1000-year return period, influenced by flat topography downstream and in the central area, resulted in widespread flooding as shown in Figure 3. Water overflowed from the levees, extending the floodplain over 6 km from the river center line. This event highlighted the need for robust flood protection and comprehensive floodplain management.

Furthermore, the simulation of the extreme event of a 1000-year return period revealed some striking outcomes. The flood's effects were largely attributed to the flat topography downstream and in the central part of the study area. As a result, extensive and substantial flooding occurred, dramatically extending the floodplain downstream by over 6 km from the river's centerline to the valley region. During this extraordinary event, the levees reached their capacity and began to overflow, causing a dispersion of water across the affected area.

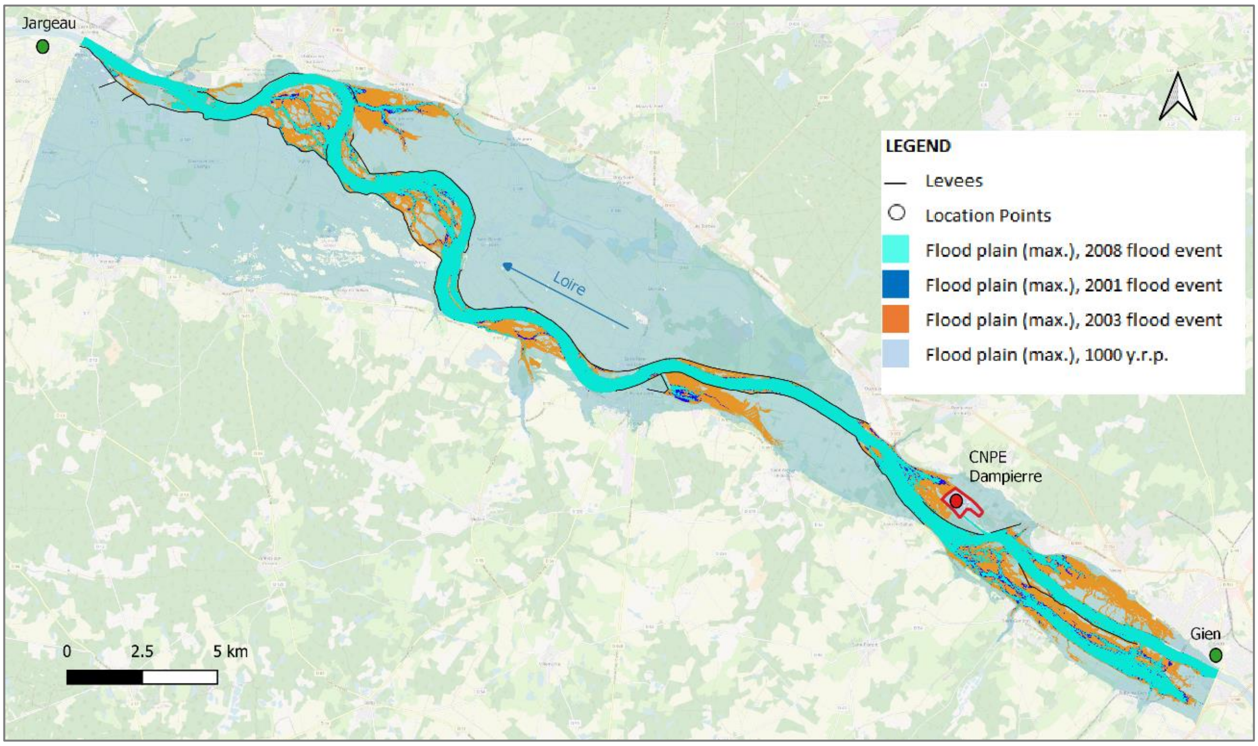


**Figure 3**: Floodplains along the Loire river between Gien and Jargeau, simulation results of flood events of 2001, 2003, 2008 and calculated 1000-year return period.

### *3.1.2. Water depths and velocities*

The analysis of water depth offers valuable insights into the magnitude and distinctions among the described flood events. Figure 4, showcases the maximum water depth and velocities attained during the flood events of 2003 and 1000-year return period. Comparing water depth, the event of 1000-year return period stands out prominently, reaching approximately 9 m average on the center line of the riverbed.

In the simulation of the two scenarios, a direct correlation was observed between the severity of the flood event and the velocities recorded. The historical event show velocities exceeding 2 m/s on the riverbed, while the flooded areas experienced lower velocities below 1 m/s. This insight into the varying velocities provides valuable context for understanding the dynamics of water flow and even sediment presence. However, for the 1000-year return period flood event simulation, velocities exceeding 3 m/s in few areas along the riverbed were observed.

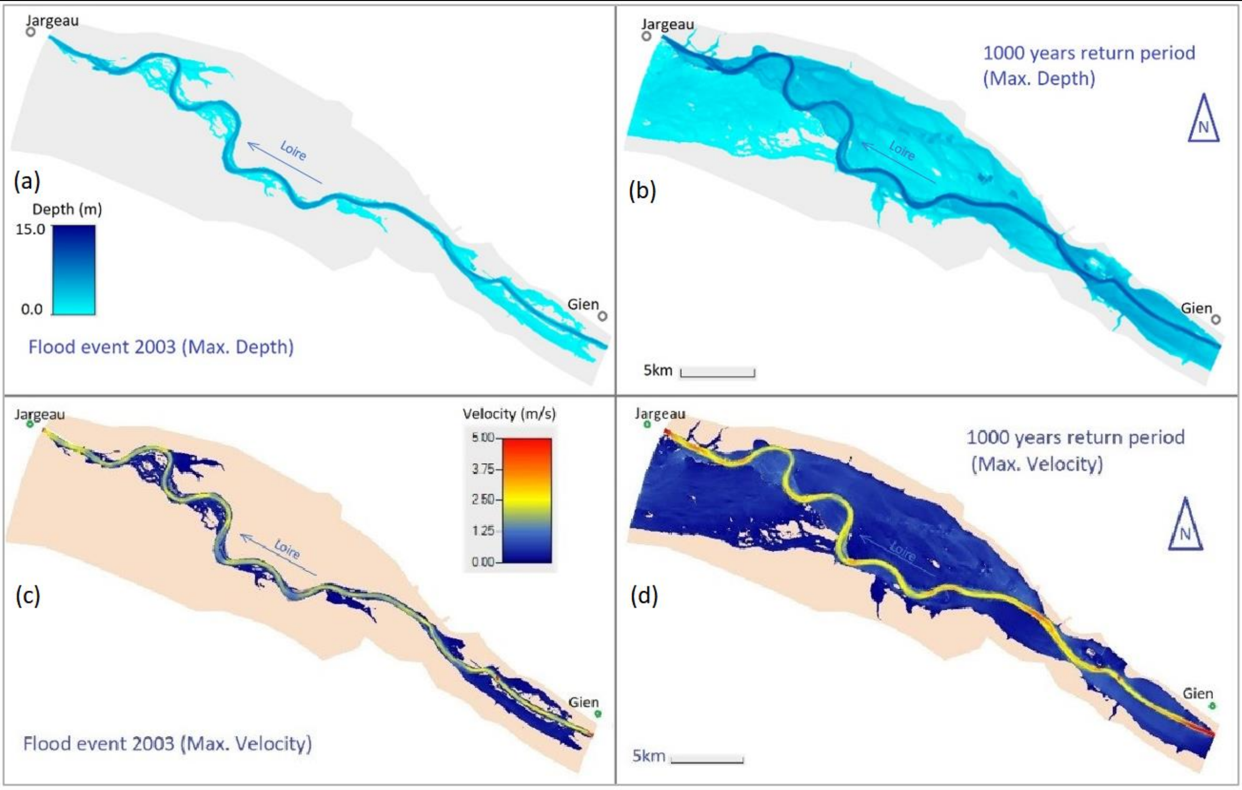


**Figure 4**: Simulation results for the Loire river - 2003 Flood Event and 1000-Year Return Period. Shows maximum water depths (a, b) and velocities (c, d) in the region between Gien and Jargeau.

### 3.2. Comparison HEC-RAS vs TELEMAC-2D

In this section, a comparative analysis will be conducted between TELEMAC-2D and HEC-RAS, both software packages used in this study to construct two 2D hydrodynamic models of the Loire river. The assessment will encompass both the numerical approaches employed by the software and the results obtained from a real study case. By evaluating these aspects, insights into the strengths and limitations of each software in modeling the complex dynamics of the river are sought to be gained.

#### *3.2.1. Numerical Approach*

The governing equations, the mesh representation, and the numerical method, such as finite-element, finite-volume, or finite-difference, are the key factors that determine how effectively hydraulic models work [8].

- Governing equations

HEC-RAS and TELEMAC-2D are both based on solving the momentum SWE system, which is derived from the Navier-Stokes equations. HEC-RAS typically solves the finite difference method, while TELEMAC-2D adapts the finite element method [6]. SWEs are obtained by averaging the incompressible Navier-Stokes equations with respect to depth under the assumptions that the pressure field is hydrostatic, the free surface slopes are modest, and vertical velocities are low. Additionally, this equation ignores dispersion terms by presuming that changes in horizontal velocities with depth are not significant [9]. HEC-RAS also includes DWE, a simplified version of SWE suitable for less complex hydraulic models.

- Numerical method

HEC-RAS: The Eulerian-Lagrangian Method (ELM-SWE) and the Eulerian Method (EM-SWE) are the two approaches used to solve the SWE in HEC-RAS. The only difference between the solvers is how they handle the terms for acceleration and pressure gradient [10].

TELEMAC-2D: For the solution of shallow water equations, allows to choose between several numerical methods. First, the finite-element approach is employed to solve the Saint-Venant equations. This method is the "traditional" application of TELEMAC-2D. The second solution entails utilizing the finite-volume approach. The algorithm is clear in this instance and requires that the Courant number be restricted to 1 [11].

- Discretization - Numerical solution

Finite element models (TELEMAC-2D) express the solution as piecewise uniform, whereas finite volume (HEC-RAS) methods use linear or higher-order interpolation. The methods differ in how the model solutions are discretized. This suggests that finite element models may represent the real solution more faithfully. However, the benefit of the piecewise linear method for finite volumes is the capacity to express shocks and the simplification of the model structure [9].

- Mesh Representation

TELEMAC-2D: uses triangular (or quadrilateral) finite elements to solve the equations on non-structured grids. Due to the structure of the finite element mesh, it is possible to fit components of different sizes within a defined boundary, allowing for high resolution in regions with increasing bed slope or narrow channels and low resolution in areas where detailed information is not required [12]. The software calculates two horizontal velocity components and the flow depth at each computational node of the mesh [13]. A system of irregular triangular components that combined the mesh for the channel and floodplains was used to discretize the entire modeling area as shown in Figure 5 (b). The DEM and river bathymetry data were used to generate the mesh using the Blue-Kenue program.

HEC-RAS: Variability can be simulated across and along the flow route using 2D modeling with HEC-RAS. Each grid cell uses the underlying topography data with less resolution loss referred as sub grid model, discretizing the model region into grid cells as represented in Figure 5 (a). The computation time is improved as a result of this. A detailed hydraulic property table, including the relationship between elevation and volume, area, and elevation, among others, is generated by HEC-RAS for each cell and cell face. Larger cells are created as a result, which can use higher time steps and retain topographical information. Depending on the topography and flow resistance dictated by the type of land use, the water can move in either direction [14].

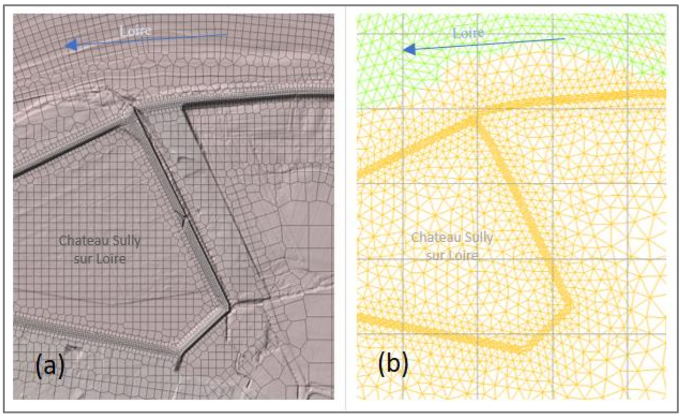


**Figure 5**: Mesh Representation of the Loire Hydrodynamic Model, area of the Chateau Sully sur Loire. HEC-RAS mesh (a), TELEMAC-2D mesh (b)

### *3.2.2. Results Analysis*

- Floodplains

In this section, a comparison of the floodplains obtained from the TELEMAC-2D hydrodynamic model and the HEC-RAS model of the Loire river has been conducted, specifically for the historical flood event of 2003.

Figure 6 reveals some notable differences between the two models (Areas 1 and 2). The TELEMAC-2D simulation exhibits a broader coverage of the flooded area, while a significant discrepancy in the results is observed within the Area 1, located at the central part of the river stretch. In the HEC-RAS simulation, this mentioned area near to “Chateau Sully sur Loire” is flooded, which is not replicated in the TELEMAC-2D simulation. This discrepancy arises because HEC-RAS takes into consideration an existing narrow channel next to the castle, allowing water to intrude into this specific area.

The comparison of flood areas in Table 2 shows that TELEMAC-2D provides larger flood areas for both the 2003 flood event and the 1000-year return period. This is mainly due to TELEMAC's even distribution of water across each cell. In contrast, HEC-RAS exhibits partial wet cells influenced by topography, resulting in more clearly defined floodplain areas. However, this topographical influence also impacts water levels, causing greater water dispersion and subsequently lower water levels, which align with the principle of mass conservation.

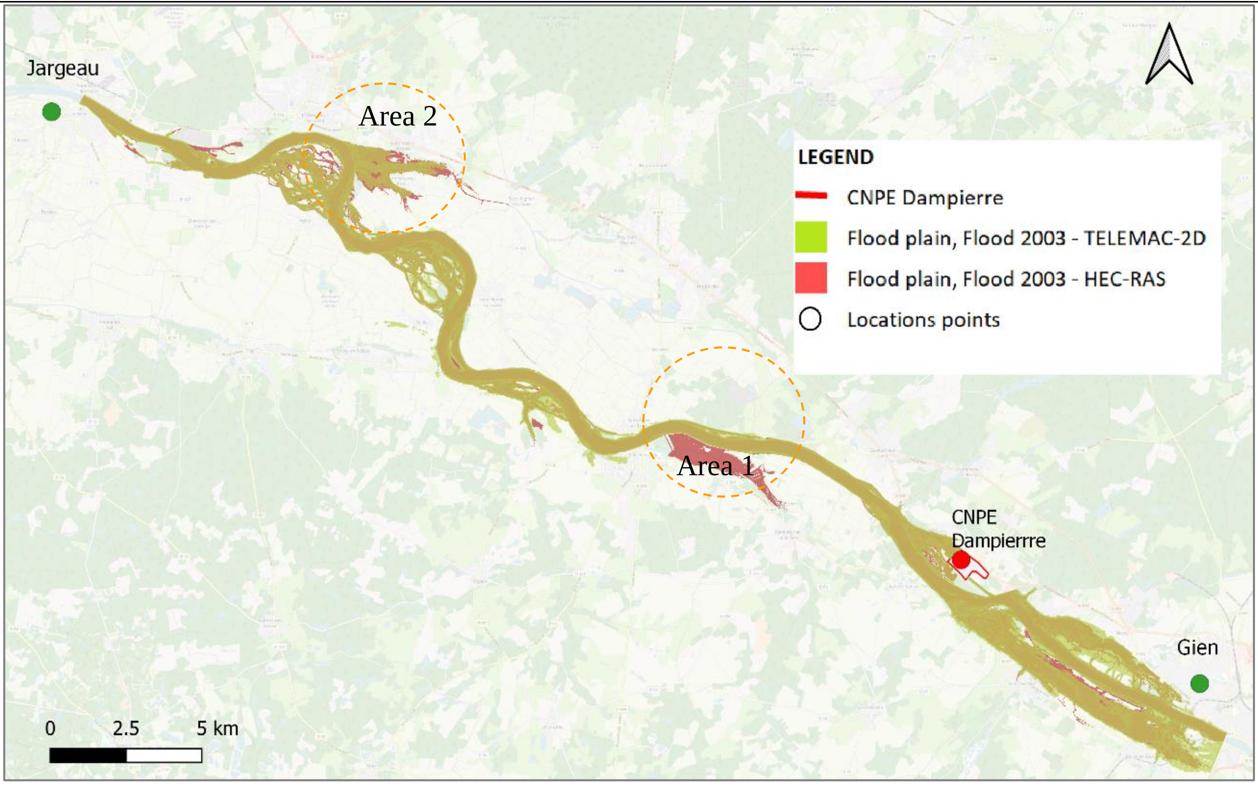


**Figure 6**: Floodplain comparison between HEC-RAS and TELEMAC-2D models for the simulations of the historical event of December 2003.

**Table 2**: Flooded Areas Results comparing HEC-RAS and TELEMAC-2D

| **Results** | | **HEC-RAS** | | **TELEMAC-2D** | |
|---|---|---|---|---|---|
| **Flood Event** | Data | Flood Area ($km^2$) | Flood Area (%) Relation with total study area | Flood Area ($km^2$) | Flood Area (%) Relation with total study area |
| **December, 2003** | WSE max. | 48.08 | 14.78 | 50.77 | 15.61 |
| **1000-year return period** | WSE max. | 205.55 | 63.21 | 211.92 | 65.17 |
| **Study Area*** | Total Area | 325.18 | 100.00 | - | - |

- Water Depth

The comparison of water levels in the centerline profile of the Loire river between Gien and Jargeau (Figure 7), based on the results obtained after 132 hours of simulations for the 1000-year return period flood event, reveals remarkably similar results from both hydrodynamic models.

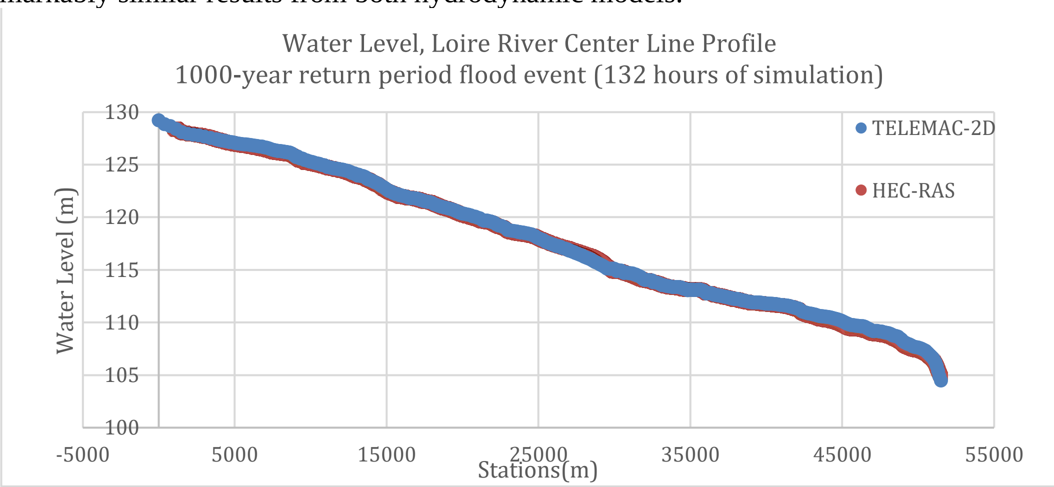


**Figure 7**: Comparison of water levels at the centerline profile obtained using the 2D models HEC-RAS and TELEMAC-2D after 132 hours of simulation for the 1000-year return period flood event.

- Levee Breaches

In the examination of both HEC-RAS and TELEMAC-2D models, a comprehensive analysis of 16 breach scenarios was conducted for each. The findings from these scenarios revealed remarkable similarities in the behavior of water depth across the majority of the cases in both software outputs. This noteworthy resemblance between the results of the two models indicates a certain level of consistency and agreement in capturing the dynamics of water depth during various breach scenarios.

In Figure 8, a comparative analysis of maximum water depth results obtained from the mentioned models is presented. Notably, the water depth values from HEC-RAS consistently appear slightly higher than those obtained from TELEMAC-2D. Despite this difference, both models demonstrate similar behavior in water dynamics, displaying a congruent pattern in their responses.

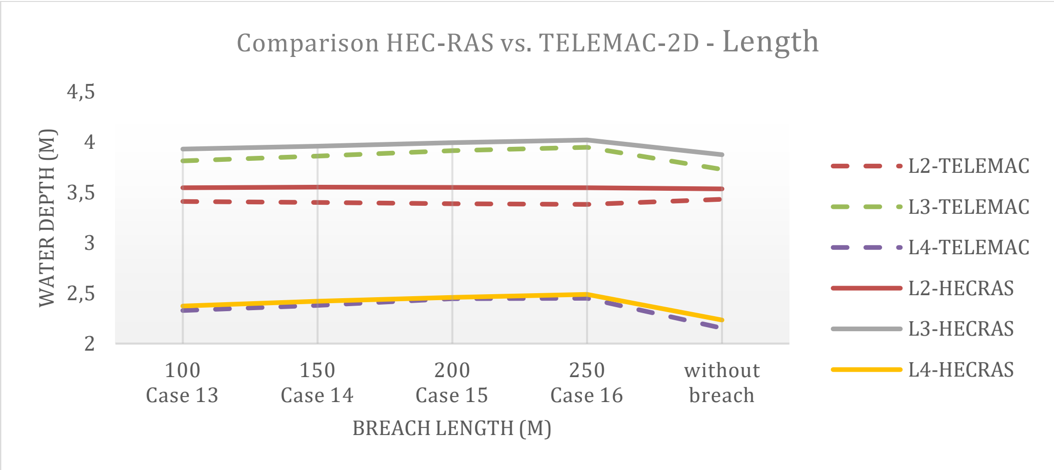


**Figure 8**: Comparative Length Analysis of HEC-RAS and TELEMAC-2D Results for Water Depth: Cases 13, 14, 15, 16, and 1000-Year Return Period, Including Simulation Without Levee Breaches.

## 4. CONCLUSIONS

This study has provided a comprehensive analysis of HEC-RAS 2D and TELEMAC-2D hydrodynamic models in the context of modeling Loire river floods, highlighting their flexibility, adaptability, and the impact of key parameters such as equation selection and time step. The comparison of breach scenarios and floodplain simulations has revealed valuable insights into their performance to model abs analyse floods.

In HEC-RAS 2D-hydrodynamic modeling, the selection between the Shallow Water Equation (SWE) and Diffusion Wave Equation (DWE) affects stability, computational time, and water levels. Comparative simulations revealed variations in water levels of the riverbed at 21 control points along the river. On average, there was a 0.17 m difference, ranging from 0.06 m to 0.32 m, with SWE resulting in higher water levels.

The time-Step parameter was found to have a crucial impact on model stability and computational efficiency. It also influenced water levels until convergence. When comparing 2 and 30 second time steps, an average water level variation of approximately 0.03 m across 21 control points, with variations ranged from 0.02 to 0.11 m. Results indicate that, in this particular case model, model stability is achieved with a 5-second time step.

In the analysis of simulated breach cases, despite slight differences, flooded areas remained consistent. An inportant distinction between breach and non-breach scenarios lies in flood dynamics and the timing of water arrival. In non-breach cases, water levels arrive later but rise faster in the floodplains, reaching a depth of 1 m 2.7 times more rapidely than in the breach scenario.

Both HEC-RAS and TELEMAC-2D have effectively demonstrated their capacity to represent flood events with flexibility and adaptability, grounded in the principles of Saint-Venant equations. HEC-RAS offers a choice between SWE and DWE using a finite-volume scheme, while TELEMAC-2D, in this study, uses a finite-element scheme with triangular elements. The congruence of results between these software tools underscores their robustness in flood research.

TELEMAC-2D requires to use of additional software (such as Blue-Kenue) for enhanced data management, analysis, and result visualization, while HEC-RAS offers an integrated and user-friendly ecosystem that streamlines the modeling process, providing modelers with a dynamic experience.

HEC-RAS stands out due to its inclusion of sub-grid technology, which preserves detailed topographical information within discretized cells. This feature allows for finer result details and better understanding of the area and water behavior during modeling and post-processing. It was crucial to accurately identify all the flood areas in this study.

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## 6. REFERENCES AND CITATIONS

[1] Ramos, M.H., Perrin, C., Andréassian, V., Olivier Delaigue, Julie Viatgé (2017). Assessment report on the 2016 flood event on the Seine and Loire basins (France). Final report. European Flood Awareness System (EFAS) dissemination centre, Rijkswaterstaat (NL), Vigicrues network / SCHAPI (France), Irstea (France), 43 pp.

[2] Klijn, F., Samuels, P. and Van Os, A. (2008) ‘Towards flood risk management in the EU: State of affairs with examples from various European countries’, International Journal of River Basin Management, 6(4), pp. 307–321. doi:10.1080/15715124.2008.9635358.

[3] Özer, I.E., van Damme, M. and Jonkman, S.N. (2019) ‘Towards an international levee performance database (ILPD) and its use for macro-scale analysis of levee breaches and failures’, Water, 12(1), p. 119. doi:10.3390/w12010119.

[4] Maurin J., Boulay A., Piney S., Le Barbu E., Tourment R. (2012) Les brèches des levées de la Loire : brèche de Jargeau 1856. Congrès SHF Événements extrêmes fluviaux et maritimes, Feb 2012, Paris, France. SHF, 8 p.

[5] DREAL (2011) Centre Étude de dangers des digues de classe A de la Loire moyenne Étude des brèches du val d'Orléans (code C4) affaire n°125900 Janvier 2011

[6] Gharbi, M., Soualmia1 A., Dartus D., Masbernat L., (2016) ‘Comparison of 1D and 2D Hydraulic Models for Floods Simulation on the Medjerda Riverin Tunisia’ Journal of Materials and Environmental Science

[7] Pheulpin, L., Migaud, A. and Bertrand, N. (2022) ‘Uncertainty and sensitivity analyses with dependent inputs in the 2D hydraulic model of the Loire River’, Proceedings of the 39th IAHR World Congress [Preprint]. doi:10.3850/iahr-39wc2521711920221433.

[8] Shustikova, I. et al. (2019) ‘Comparing 2D capabilities of HEC-Ras and Lisflood-FP on complex topography’, Hydrological Sciences Journal, 64(14), pp. 1769–1782. doi:10.1080/02626667.2019.1671982.

[9] Horritt, M.S. et al. (2007) ‘Comparing the performance of a 2-D finite element and a 2-D finite volume model of floodplain inundation using airborne SAR imagery’, Hydrological Processes, 21(20), pp. 2745–2759. doi:10.1002/hyp.6486.

[10] Brunner G. (2023), HEC-RAS River Analysis System Hydraulic Reference Manual Version 6.4, US Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, Available at: https://www.hec.usace.army.mil/confluence/rasdocs/ras1dtechref/latest (Accessed: 26 July 2023).

[11] TELEMAC-2D, (2014) ‘TELEMAC-2D User Manual’ Available at: http://www.opentelemac.org/downloads/MANUALS/TELEMAC-2D/telemac2d_user_manual_en_v7p0.pdf

[12] Fernandes, E. H., Dyer, K. R., & Niencheski, L. F. H. (2001). Calibration and Validation of the TELEMAC-2D Model to the Patos Lagoon (Brazil). Journal of Coastal Research, 470–488. http://www.jstor.org/stable/25736313

[13] Vu, T. et al. (2015) 'Two-dimensional hydrodynamic modelling of flood inundation for a part of the Mekong River with TELEMAC-2d', British Journal of Environment and Climate Change, 5(2), pp. 162–175. doi:10.9734/bjecc/2015/12885.

[14] Ongdas, N. et al. (2020) 'Application of HEC-ras (2D) for flood hazard maps generation for Yesil (ishim) river in Kazakhstan', Water, 12(10), p. 2672. doi:10.3390/w12102672.