

Integrated Hydrological-Hydraulic Modeling for Flood Prevention in the Canche and Liane Watersheds

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Abstract

Flooding poses significant risks to communities in wetlands and densely urbanized regions, necessitating robust prevention strategies. This study focuses on the Canche and Liane watersheds in the Hauts-de-France region (northern France), aiming to develop a comprehensive flood mitigation framework. We used an integrated methodology combining hydrological modeling (via HEC-HMS and its geospatial interface, GeoHECHMS) to simulate rainfall-runoff dynamics and hydraulic modeling (using HEC-RAS and GeoHECRAS) to analyze water flow and inundation patterns. Key outcomes include the identification of high-risk zones through detailed flood hazard mapping and the evaluation of proposed protective infrastructures, such as retention basins and channel modifications. The study underscores the effectiveness of coupling hydrological and hydraulic models to predict flood extents and optimize mitigation measures. These findings provide actionable insights for policymakers and urban planners to enhance resilience in vulnerable areas. Significance: The methodology and results offer a transferable framework for flood risk management in similar regions, emphasizing the role of advanced modeling tools like HEC-HMS and HEC-RAS in evidence-based decision-making.

Keywords

Hydrological Modeling, Flood Prevention, Hauts-De-France, HEC-HMS, HEC-RAS

1. Introduction

Flooding represents one of the most severe and costly natural hazards in Europe, a threat projected to intensify with ongoing climate change and increased urbanization. The European Environment Agency (EEA) has consistently warned that

future flood damages are expected to rise significantly, impacting coastal and densely populated regions most severely. This escalating risk demands a paradigm shift in flood management, moving beyond reactive measures toward proactive strategies centered on robust predictive modeling and resilience planning.

The Hauts-de-France region is particularly vulnerable and prone to flooding, mainly due to its geographical location and unique topography [1] [2]. This challenge was tragically underscored in the Hauts-de-France region of northern France during the winter of 2023-2024. The Pas-de-Calais department, in particular, experienced flooding of exceptional intensity and scale. A rapid succession of severe rainfall events, including storms Ciaran and Domingos, delivered record precipitation totals, with some areas receiving between 400 and 800 mm in less than two months. These events occurred on soils already saturated from previous rainfall, leading to devastating and widespread inundation.

The coastal watersheds of this region, notably the Canche and Liane, are historically vulnerable to rapid and intense flooding due to their specific hydrological and geographical characteristics. While prior research has examined flood risk management policies in the Canche valley and the specific nature of “flash floods” (*crues rapides*) in northern France, the 2023-2024 events exposed the limitations of existing frameworks. This highlighted an urgent need for more integrated and predictive modeling tools capable of managing such extreme hydrological responses.

To address this gap, coupled hydrological and hydraulic modeling has become a fundamental approach in modern flood risk management. Advanced tools such as the Hydrologic Engineering Center’s Hydrologic Modeling System (HEC-HMS) and River Analysis System (HEC-RAS) are widely recognized for their efficacy. These models allow for the accurate simulation of rainfall-runoff dynamics (hydrology) and the subsequent analysis of flood wave propagation and inundation patterns (hydraulics), providing a robust basis for evidence-based decision-making.

The primary objective of this study is to develop and apply an integrated hydrological (HEC-HMS/GeoHECHMS) and hydraulic (HEC-RAS/GeoHECRAS) modeling framework specifically for the Canche and Liane watersheds. This research aims to: (1) accurately simulate the hydrological dynamics of the recent flood events, (2) generate detailed flood hazard maps for various return periods, and (3) evaluate the potential effectiveness of proposed protective infrastructures. Ultimately, this work seeks to provide a robust decision-support tool for urban planners and policymakers to enhance flood resilience in this vulnerable region.

Using a scientific approach based on hydraulic modelling and technical analyses, this work provides a de-tailed model of the causes, hydrological dynamics, impacts and institutional responses to this major event.

Hydraulic modeling constitutes a fundamental phase in flood risk management, transforming hydrological inputs into detailed spatial predictions of flood behavior. In this study, we employed the latest versions of HEC-RAS to construct

and simulate hydraulic models that provide high-resolution flood hazard and risk maps across the study area for multiple return periods [3].

Following the hydrological modeling, which generated runoff hydrographs for selected return periods, hydraulic simulations were carried out to model flood wave propagation through river channels and adjoining floodplains. The 1D modeling capabilities of HEC-RAS enabled accurate simulation of unsteady flow conditions along river reaches, efficiently capturing the dynamics of water levels and velocities within the channel network.

To enhance spatial resolution and capture the complex floodplain hydraulics, the 2D modeling features integrated in HEC-RAS, facilitated via the GEO-HECRAS extension in ArcGIS, were used. This allowed detailed representation of overbank flow, floodplain inundation extents, and flow velocity distributions across topographically diverse terrains, crucial for precise delineation of flood hazard zones.

By coupling 1D channel flow with 2D floodplain hydraulics, the combined models effectively represent critical phenomena such as levee overtopping, flood wave attenuation, and backwater effects. This integrated modeling approach ensures a comprehensive understanding of flood behavior across the catchment.

The output from these simulations—flood depth, velocity, and extent for different return periods—was used to generate flood hazard maps. These maps were subsequently overlaid with exposure and vulnerability data (e.g., land use, infrastructure locations) to develop flood risk maps. This multi-tiered mapping approach supports robust decision-making for flood mitigation planning and emergency preparedness.

The use of HEC-RAS and GEO-HECRAS offers significant advantages in terms of model accuracy, user interface improvements, and seamless GIS integration, which together contribute to improved flood risk assessments in this study [4] [5].

2. Materials and Methods

2.1. Presentation of the Study Areas

This research focuses on flood prevention strategies in the diverse and geographically significant Hauts-de-France region, with a targeted examination of two key watersheds central to the area's hydrology: the Canche and the Liane.

1. Canche Watershed

Spanning approximately 1,400 km², the Canche watershed traverses multiple municipalities before emptying into the English Channel between the coastal towns of Étaples and Le Touquet-Paris-Plage (**Figure 1**). Characterized by a 1 - 2 km-wide river valley, expansive alluvial plains, and a gentle slope, the basin's permeable lime-stone geology belies its vulnerability to flooding. Historically significant floods in 1988, 1995, 1998, and most recently in 2023 have caused extensive damage to infrastructure and residential areas, underscoring the region's risk.

2. Liane Watershed

In contrast, the Liane watershed covers a smaller area of 244 km² but features a

dense hydrological network. Originating in Quesques, the 36 km-long river flows through urbanized zones, including Boulogne-sur-Mer. This basin is prone to river overflow and surface runoff flooding, exacerbated by steep tributary gradients and complex terrain morphology. These factors create heightened challenges for flood management, particularly in densely populated areas.

Analyzing these contrasting watersheds is critical to understanding regional hydrological dynamics. The study aims to inform tailored flood prevention strategies, ensuring community resilience and safeguarding vulnerable populations. By addressing the unique risks of each basin, this research contributes to sustainable solutions for mitigating flood impacts in Hauts-de-France [3] [6].

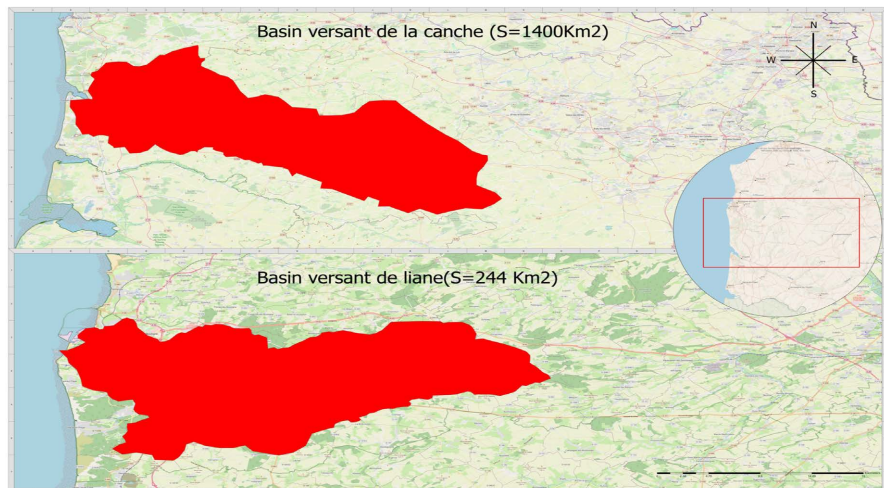


Figure 1. Location map illustrating the Canche and Liane watersheds.

2.2. Data Used

Hydrometeorological data collection was critical for calibrating and validating hydrological and hydraulic models [7]. For the Canche watershed, rainfall stations used are located at Humières, Saint-Michel-sur-Ternoise, Lebiez and Le Touquet-Paris-Plage (Figure 2). Hydrometric stations used are located at Étaples, Brimeux and Hesdin (Figure 2). With regard to the Liane watershed, three rain gauge stations were available in Henneveux, Desvres and Wirwignes respectively (Figure 3). A single hydrometric station located in Isques was present and in use (Figure 3). These stations provided reliable, high-resolution datasets to model the hydrological regimes of both watersheds.

High-resolution LiDAR surveys (0.5 m), sourced from the Géoservices France platform, were used to precisely define terrain elevation, slopes, and potential flood-plain zones. Unlike satellite imagery-based approaches, this study utilizes detailed land use and soil to characterize soil infiltration capacity, surface runoff patterns, and flood vulnerability.

This comprehensive dataset enabled highly accurate hydrological and hydraulic simulations, facilitating the identification of at-risk zones and the proposal of targeted flood protection measures.

The methodological framework combines ArcGIS Pro, ArcHydro, and HEC-HMS, integrated with rainfall frequency analysis for generating Intensity-Duration-Frequency (IDF) curves. The workflow is structured as follows:

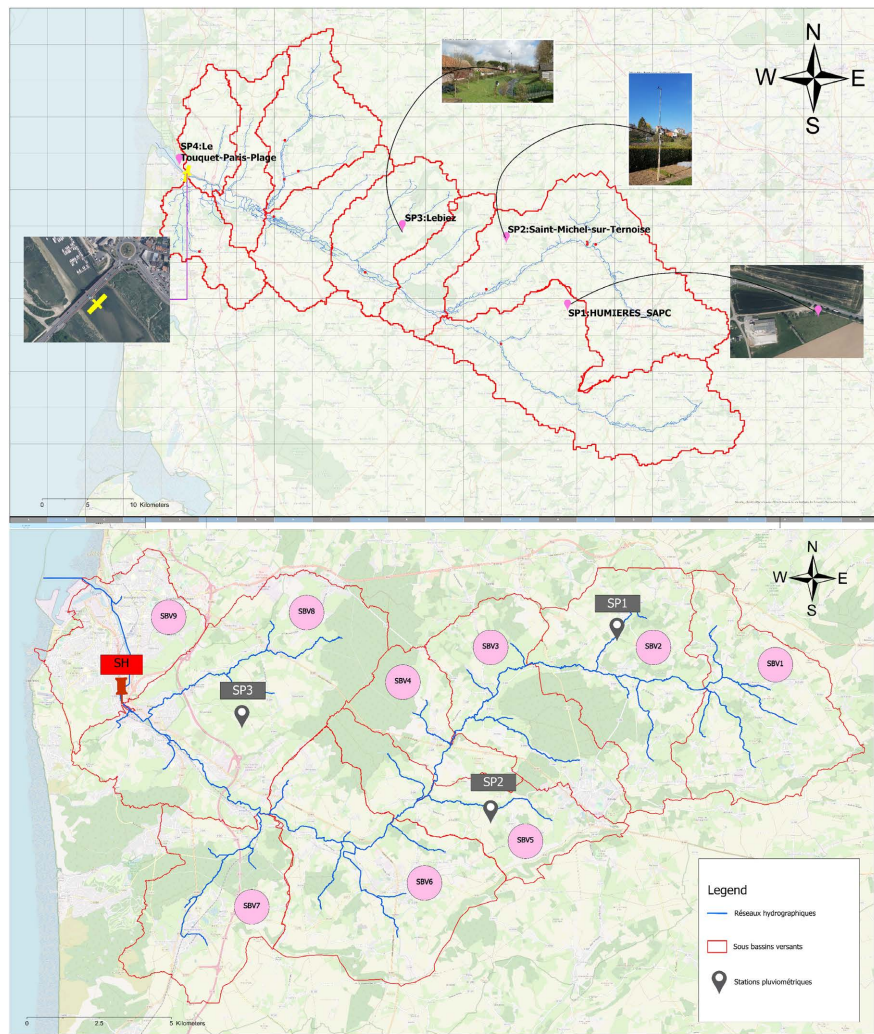


Figure 2. Location of rainfall and hydrometric stations in the Liane and Canche watersheds.

2.3. Software Used

The HEC-HMS model, developed by the US Army Corps of Engineers, is a semi-distributed (*i.e.*, physically and conceptual) model [8]. The model is specifically created to simulate a dendritic watershed-type system and can serve multiple purposes such as urban flooding simulation, analyzing flood frequency, planning flood warning systems, assessing reservoir spillway capacity, and stream restoration. The model consists of several modules that perform distinct functions such as loss estimation, open channel routing, runoff alteration, and analysis of meteorological data. Additionally, there are separate modules that can be used for estimating different components of the runoff process (*i.e.*, runoff volume, direct runoff, and base flow). These individual modules can be used independently for

their respective purposes [9]. The HEC-HMS model consists of five major components including basin models, meteorological models, control specifications, input data, and outputs. The estimation of rainfall-runoff from simulation can be performed in the basin model given input from the meteorological model. The control specifications describe the period and time step of the simulation run. And the input data components, such as time-series data, set of data, and gridded data are often required as a parameter or boundary conditions in the basin and meteorological models. Finally, the model output data are presented through the graphical user interface [10].

The performance of model should be evaluated for the extent of its correctness, consistency and adaptability [11] [12]. In this study the HEC-HMS model performance was evaluated through visual examination of the simulated and observed hydrographs and through a set of objective functions that measure the goodness-of-fit between simulated and observed hydrograph. In addition to this, the model was evaluated using statistical measures to determine the quality and reliability of predictions when compared to observed values. Efficiency criteria such as Nash and Sutcliffe simulation efficiency (NSE), coefficient of determination (R^2), percent error peak flow (PEPF), percentage (%) error in the total runoff volume (RVE) and percentage bias (PBIAS) were used to evaluate the model performance [13].

NSE and R^2 were used to evaluate the model ability to reproduce the pattern of the observed hydrographs. The percent error peak flow measures the agreement between the magnitudes of observed and simulated peak values. The Nash-Sutcliffe coefficient of efficiency (NSE) is estimated by:

$$NSE = 1 - \frac{\sum_{i=1}^n (Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^n (Q_{obs,i} - \bar{Q}_{obs,i})^2}$$

where NSE is Nash-Sutcliffe coefficient of efficiency, $Q_{obs,i}$ is the observed discharge at the time step i , $\bar{Q}_{obs,i}$ is the mean of the observed discharge, $Q_{sim,i}$ is the simulation discharge at the time step i , and n is the number of observations. NSE ranges between $-\infty$ and 1 with $NSE = 1.0$ being the target value [13].

Values between 0.6 and 1.0 are generally viewed as acceptable level of performance, but values $NSE = 0$ indicate that the mean observed value is a better predictor than the simulated value of hydrological data, which indicates unacceptable performance. As all terms are defined previously, the coefficient of determination (R^2) is estimated by:

$$R^2 = \frac{\left[\sum_{i=1}^n (Q_{sim,i} - \bar{Q}_{sim,i})(Q_{obs,i} - \bar{Q}_{obs,i}) \right]^2}{\sum_{i=1}^n [(Q_{sim,i} - \bar{Q}_{sim,i})^2] \sum_{i=1}^n [(Q_{obs,i} - \bar{Q}_{obs,i})^2]}$$

where, Q_{avg} is the average of the observed data ($m^3 \cdot s^{-1}$) for the relevant being evaluated; Q_i is the observed discharge ($m^3 \cdot s^{-1}$); n is the number of observations, and Q' is the simulated discharge ($m^3 \cdot s^{-1}$). NSE values can vary from $-\infty$ to 1. In general, the model is more accurate if NS is closer to 1. The NS is sensitive to

extreme values and may produce sub-optimal results when the data set holds large outliers in it:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (O_i - S_i)^2}$$

The percentage of bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. The optimal value of PBIAS% is 0, with low-magnitude values indicating an accurate model simulation. Positive values show under estimation bias, and negative values indicate overestimation bias which can be calculated as,

$$\text{PBIAS} = \frac{\sum_{i=1}^n (Q_{o,i} - Q_{s,i})^2}{\sum_{i=1}^n (Q_{o,i})} \times 100$$

To verify the model performance under different watershed conditions, the simulated hydrograph is compared with the observed flow data. The HEC-HMS model comprises different loss methods specifically designed for event-based modeling and continuous runoff simulation. The grid-based and soil moisture type loss methods are two types that require a large number of input parameters, whereas the deficit and constant loss methods are simpler. Conversely, the transformation methods offered by the HEC-HMS model are complex and require a significant number of input values, making it challenging to apply them to ungauged watersheds where these parameters may not be available [14]. Various researchers have successfully applied the Soil Conservation Service (SCS) unit hydrograph, Snyder unit hydrograph, and Clark unit hydrograph for rainfall-runoff simulation [15] [16].

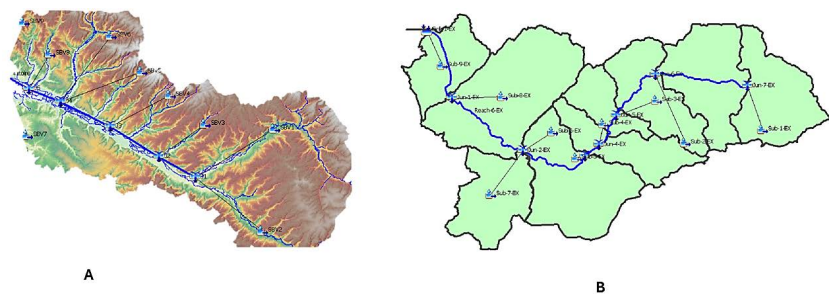


Figure 3. Schematic representation of the Canche, A and Liane, B watersheds, delineated into nine sub-watersheds each, using HEC-HMS and GEOHHECHMS models, respectively of rainfall.

The SCS method has certain advantages, including its ability to perform well in different environments, it requires only a few variables such as lag time, land use, and slope, which makes calculation easier, and its ability to produce results that are as good as those of more complex models [17].

The study involves the application of two distinct hydrological models for the Can-

che and Liane watersheds. For the Canche watershed, a semi-distributed model was developed using HEC-HMS, while for the Liane watershed, the GEOHHECHMS software was employed. Each watershed was further subdivided into nine sub-watersheds to enhance the spatial representation of hydrological processes. The delineation of sub-watersheds and the extraction of physical characteristics, such as drainage area, channel length, and slope, were performed using digital elevation models (DEM) in conjunction with the respective modeling tools. The calibration and validation of the models were conducted based on observed hydrometric data to ensure accurate runoff simulations through loss, transform, and baseflow processes.

2.4. Characterization of Historical Hazard and Flood Intensity

This vulnerability of the Canche and Liane basins is particularly critical as the areas they cross—including major towns like **Liane** and **Canche** concentrate **critical infrastructure**, such as large industrial sites, commercial centers, and essential social facilities (e.g., hospitals, hotels). Flooding in these territories is not merely an environmental hazard but a major socio-economic risk (**Figure 4**). Consequently, the accurate predictive modeling proposed in this study is essential not only for flood mapping but also as a fundamental tool for **damage analysis** (monetary evaluation). This will allow decision-makers to prioritize investments and implement effective and economically viable **Nature-Based Solutions (NBS)** to maximize urban protection and resilience.

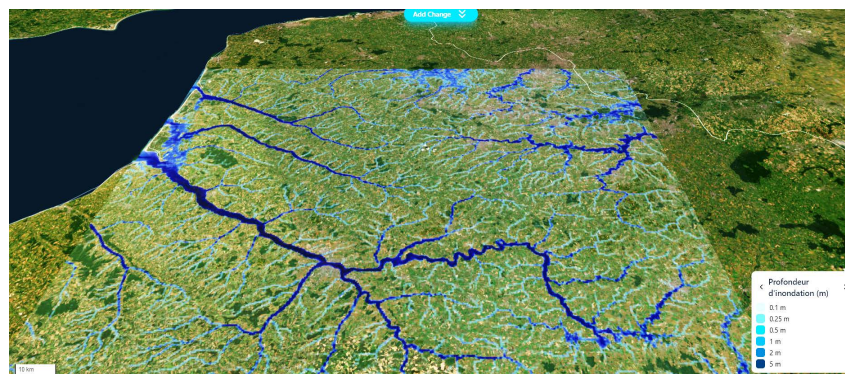


Figure 4. Simulation of the Historical Flood Event and Hazard Mapping (Canche and Liane Watersheds).

3. Results

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.1. HEC HMS Modelling Result for Observed Rainfall Products

Following the development of the hydrological model, an initial simulation is performed to compare the simulated hydrograph with the observed hydrograph. This

comparison assesses the model's ability to reproduce the hydrological behavior of the watershed. Specifically, differences between the two hydrographs are quantified using hydrological performance metrics, such as the Nash-Sutcliffe Efficiency (NSE) and the Root Mean Square Error (RMSE). Subsequently, an optimization process is undertaken, where model parameters are iteratively adjusted to minimize these discrepancies and improve the model's fit to the observed data.

The calibration of hydrological models requires systematic adjustment of key parameters to minimize discrepancies between simulated and observed hydrographs. In this study, we optimized critical parameters to better represent the hydrological processes of the Canche and Liane catchments, focusing on both physical realism and predictive accuracy [18].

3.1.1. Land Use and Infiltration Dynamics

The Soil Conservation Service Curve Number (SCS-CN) method's Curve Number (CN) parameter was calibrated to refine runoff estimation. This coefficient, which reflects soil permeability and land cover characteristics, directly governs infiltration capacity and surface runoff generation. Adjusting CN values improved the model's ability to capture spatial variability in hydrological responses across heterogeneous soil types and land use patterns.

3.1.2. Basin Response Timing

The Lag Time (LagT) parameter was optimized to simulate the delay between peak rainfall and subsequent flood peak emergence. This calibration ensured accurate representation of catchment response dynamics, particularly for rapid rainfall events where timing errors could skew flood prediction accuracy (Table 1).

Table 1. Parameter values adjusted for March 2020 events.

SubWatershed	CN	Lagtime (min)
SW1	60.713	1241.4
SW2	51.551	1819.2
SW3	62.34	623.12
SW4	74.894	501.31
SW5	37.456	710.57
SW6	47.562	607.12
SW7	74.894	552.71
SW8	84.77	451.71
SW9	85.65	633.01

3.1.3. Flood Wave Propagation

Flow routing was modeled using the Muskingum method (Table 2), with two core parameters:

K: Represents the travel time of floodwaters through the river reach, controlling the speed of peak discharge propagation.

X: Governs flood wave diffusion, balancing attenuation and dispersion effects. Precise calibration of K and X was critical for replicating observed hydrograph shapes, including peak magnitude, timing, and recession limb behavior.

Table 2. K, X parameter values adjusted for March 2020 events.

Reach	Parameter	Units	Initial values	Optimizes values
R1	Muskingum - K	HR	0.2	0.016
R1	Muskingum - X	°	0	0.001
R3	Muskingum - K	HR	0.2	0.016
R3	Muskingum - X	°	0	0.01
R2	Muskingum - K	HR	0.2	0.016
R2	Muskingum - X	°	0	0.001

3.1.4. Hydrological Model Performance Assessment

The hydrological model was evaluated at the Étapes hydrometric station (Canche watershed), a strategic location for analyzing flow dynamics and their interplay with precipitation and local hydrological processes. Model reliability was quantified using four statistical metrics:

- 1) Coefficient of determination (R^2): Measures the proportion of observed variance explained by simulations.
- 2) Nash-Sutcliffe efficiency (NSE): Assesses predictive accuracy relative to the mean of observations.
- 3) Root means square error (RMSE): Quantifies the magnitude of residual errors.
- 4) Percentage bias (PBIAS): Identifies systematic over- or underestimation tendencies.

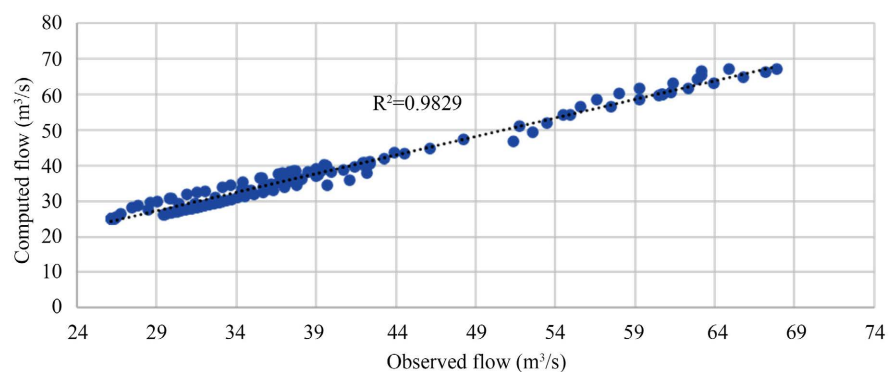


Figure 5. Regression curve for the Calibration phase.

1. Calibration Performance

During calibration, the model demonstrated exceptional agreement with observed flows:

- 1) $R^2 = 0.98$, indicating that 98% of flow variability was captured (**Figure 5**).

2) NSE = 0.97, reflecting near-perfect replication of daily hydrograph dynamics.
 3) RMSE = 0.2 m³/s, highlighting minimal dispersion between simulated and observed values.

4) PBIAS = -3.22%, suggesting a marginal underestimation of flows, well within acceptable thresholds for hydrological applications [14].

2. Validation Robustness

The model was validated on an independent timeseries to evaluate generalizability:

1) R² improved to 0.984, confirming a robust linear relationship between predictions and observations (Figure 6).

2) NSE increased to 0.98, surpassing calibration-phase performance.

3) RMSE decreased to 0.1 m³/s, demonstrating enhanced precision.

4) PBIAS shifted to +1.24%, revealing a negligible overestimation with no significant systematic bias.

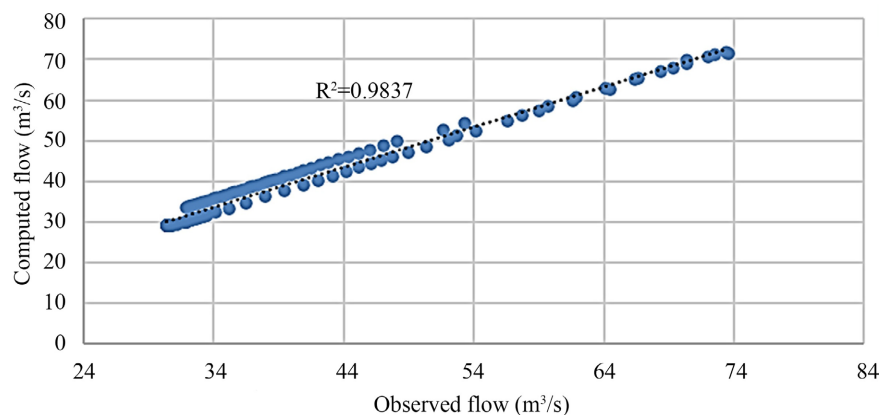


Figure 6. Regression curve for the Validation phase.

According to established criteria [19], a model is deemed “excellent” when $NSE > 0.75$, $R^2 > 0.75$, and $|PBIAS| < 10\%$. This study’s results (NSE: 0.97 - 0.98, R^2 : 0.98 - 0.986, PBIAS: ± 1.24 - 3.22%) exceed these benchmarks, con-firming exceptional predictive for floodplain modeling, the 2D module in HEC-RAS 6.6 utilizes a computational mesh with differentiated cell sizes applying a finer mesh of 2 m \times 2 m in hydraulically sensitive and urbanized areas, and a coarser mesh of 5 m \times 5 m in less complex regions. This approach optimizes the balance between simulation accuracy and computational efficiency come due to temporal variability in hydrological drivers—underscores the model’s stability under differing climatic or seasonal conditions.

The validated model provides a robust tool for:

1) Real-time flood forecasting, leveraging its ability to resolve peak flows and recession limbs with high fidelity.

2) Integrated watershed management, including scenario testing of land-use changes or climate impacts.

3) Flood Risk Prevention Plans (PPRIs), informing infrastructure design and

emergency response strategies.

3.2. Hydraulic Modeling and Flood Hazard Mapping HEC-HMS

The hydraulic modeling performed using HEC-RAS 6.6 allowed the generation of detailed flood hazard maps for various return periods across the study area. The simulation results highlight critical areas exposed to significant flood hazards due to river overflows and floodplain inundation, providing essential insights into spatial patterns of vulnerability (Figure 7).

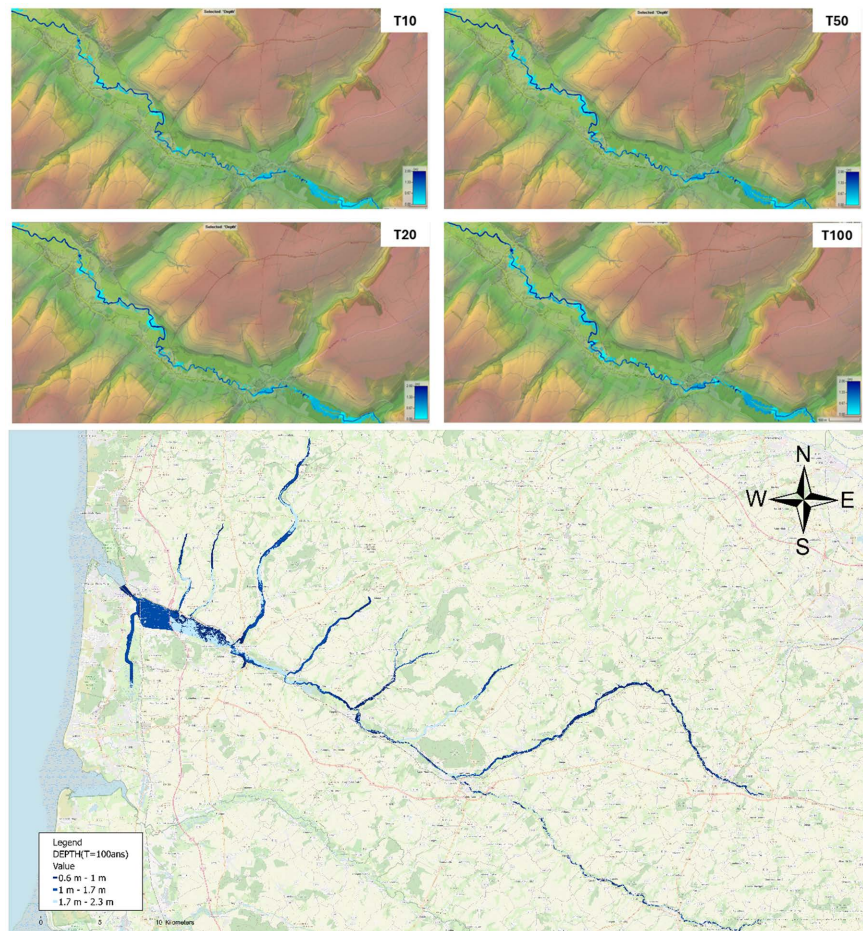


Figure 7. Flood hazard maps were generated for different return periods curve for the Validation phase.

The results for the Canche River basin indicate a pronounced flood hazard, particularly in the upper reaches of the catchment, where hydraulic simulations show substantial overbank flow during high period flood events (e.g., 50-year, 100-year, and extreme scenarios). The upstream sector exhibits marked floodplain inundation, primarily due to the steep topography, limited channel capacity, and the concentration of flow volumes generated by intense rainfall events and upstream catchment contributions.

This hydraulic behavior leads to frequent overtopping of riverbanks, resulting

in extensive flood propagation into adjacent low-lying areas. Consequently, the city of Canche—located in proximity to these upstream reaches—faces heightened vulnerability to riverine flood hazards. The simulations demonstrate that during peak events, floodwaters rapidly inundate the peri-urban and urban zones, exacerbating the risk to residential areas, critical infrastructure, and transportation networks.

Furthermore, the modeling reveals that the combination of high discharges, limited floodplain storage, and constricted channel geometry upstream of the urban core creates hydraulic bottlenecks that intensify flood impacts in the city. The flood hazard maps developed illustrate extensive inundation depths and high flow velocities within the urban perimeter of Canche, underlining the urgent need for targeted flood mitigation measures, such as structural defenses, retention basins, and early warning systems.

These findings emphasize the necessity of integrating hydraulic modeling outputs into spatial planning, emergency preparedness, and risk communication frameworks to enhance flood resilience in the Canche catchment, particularly focusing on the upstream vulnerabilities that directly influence urban flood risks.

4. Discussion

The hydraulic modeling outputs generated using HEC-RAS 6.6—including flood depth, velocity, and hazard classification maps for various return periods—were further exploited to assess flood risk levels, following the methodology outlined in the Australian Disaster Resilience Handbook [20] and associated guidelines for flood risk assessment.

The flood hazard assessment results were integrated with exposure and vulnerability data to develop flood risk maps, applying the Combined Hazard Curves-Vulnerability Thresholds Classification Limits approach recommended by the Australian Disaster Resilience Handbook - Managing the Floodplain [20].

This approach provides a structured framework for classifying areas based on both hydraulic hazard parameters (depth, velocity, debris factor) and vulnerability thresholds, allowing for the identification of zones where human safety, critical infrastructure, and community assets are at significant risk [21] [22].

Based on the hydraulic modeling outputs generated through HEC-RAS 6.6, the flood risk assessment for the Canche River catchment was performed using the Combined Hazard-Vulnerability Classification methodology outlined by the Australian Disaster Resilience Handbook [20]. The risk analysis integrated flood hazard parameters—including depth, velocity, and debris factor—with land use data, population exposure, and infrastructure sensitivity to identify areas of critical flood risk (Figure 8).

The results reveal that the upper and mid-sections of the Canche River basin exhibit particularly high flood risk levels, driven by intense overbank flooding, high flow velocities, and the presence of vulnerable urban settlements and critical infrastructure. The city of Canche is identified as a high-priority risk zone, where

the confluence of significant flood hazard and dense urban exposure creates conditions of extreme flood risk during high return period events (e.g., 50-year and 100-year floods).

The flood risk map for the Canche River catchment (**Figure 8**) clearly delineates the spatial distribution of risk classes, highlighting:

1) Areas of extreme risk (red zones) where flood depths exceed 1.5 meters with high flow velocities, directly impacting urban neighborhoods, transportation nodes, and essential services.

2) Areas of high to moderate risk (orange and yellow zones) affecting peri-urban and agricultural lands, where flood hazards remain significant but with lower vulnerability profiles.

This comprehensive risk mapping underscores the necessity for targeted flood mitigation interventions, land use regulation, and emergency preparedness measures, particularly focusing on the urban core of Canche and its immediate upstream sectors.

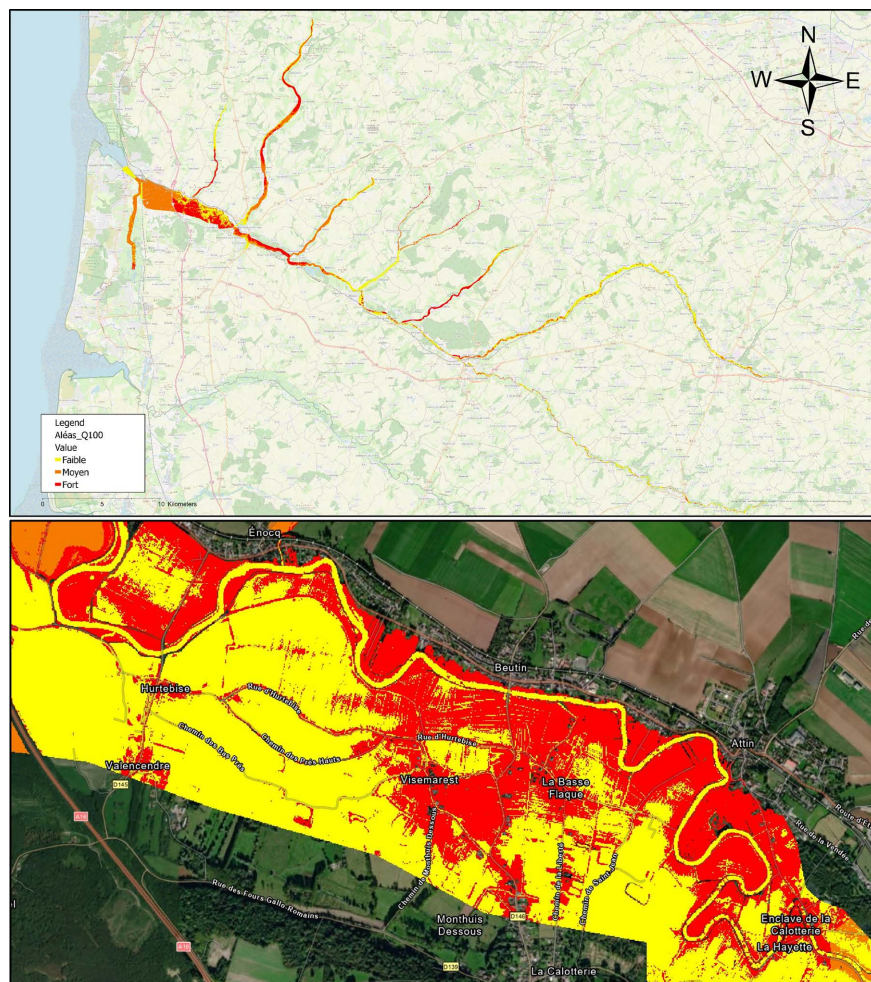


Figure 8. Flood risk map for the Canche River catchment developed using HEC-RAS 6.6 hydraulic modeling outputs combined with vulnerability thresholds according to the Australian Disaster Resilience Handbook [20].

4.1. Model Validation and Advancement of Local Understanding

This study successfully implemented a robust coupled hydrological-hydraulic modeling framework (HEC-HMS and HEC-RAS), achieving high accuracy as demonstrated by Nash-Sutcliffe Efficiency coefficients greater than 0.85 during the calibration phase. This high performance validates the effectiveness of distributed rainfall-runoff modeling approaches in highly reactive coastal catchments, corroborating earlier findings on the applicability of HEC-HMS models across diverse hydrological contexts [3].

The spatial analysis of the simulated floods, particularly the extreme event of 2023-2024, significantly refines existing knowledge regarding the region's specific flood vulnerability. While previous work [1] highlighted the complexity of flood risk management in the Canche valley, our mapping provides unprecedented spatial resolution. It precisely identifies areas prone to overbank flooding and hydraulic stagnation mechanisms. Furthermore, our results confirm the challenging nature of "flash floods" (*crues rapides*) previously identified in Northern France [2], where short response times necessitate reliable and rapid forecasting tools.

4.2. Differentiated Flood Impact and the Evolution of Resilience Strategies

Our detailed hazard maps reveal a differentiated impact across the territory, highlighting a critical tension between urban environments and natural floodplains.

On one hand, the inundation of urban areas is of paramount concern. Our simulations show that flood depths directly affect critical infrastructure (large industrial sites, commercial hubs, and essential social facilities). This intensifies the socio-economic risk, pointing to the limitations of historical resilience efforts. These efforts, often centered around structural measures (e.g., levees and channelization) driven by the EU Flood Directive, can inadvertently create a false sense of security or merely transfer the flood risk downstream.

On the other hand, a crucial aspect of this discussion is the functional role of wetlands. These areas, while inherently prone to flooding, are vital blue-green infrastructure essential for basin resilience. Our hydraulic simulations underscore their function as hydraulic sponges, demonstrating their capacity to attenuate and delay flood waves before they impact urbanized zones. Consequently, the conservation and restoration of these wetlands, as opposed to conventional "grey" infrastructure development, must be prioritized in contemporary resilience strategies and sustainable land-use planning.

4.3. Proposal for a Robust and Transferable Methodological Framework

A key contribution of this research is the establishment of a robust and transferable methodological framework for flood risk management in similar coastal regions. This framework, fully demonstrated through the application to the Canche and Liane basins, consists of four key phases:

1) Preparatory Phase: Systematic use of high-resolution Digital Elevation Models (DEMs) and precise land-use data to define physical basin parameters.

2) Hydrological Phase: Application of the HEC-HMS model to accurately estimate flood hydrographs across critical confluences.

3) Hydraulic Phase: Coupling of the HEC-RAS model (integrating 1D channel flow with 2D floodplain hydraulics) to generate high-resolution hazard maps (depth and velocity).

4) Stakeholder Analysis Phase: Overlaying hazard maps with exposure data (critical buildings, economic assets) to produce actionable risk maps.

This integrated process is readily scalable and adaptable to other similar European coastal catchments characterized by rapid hydrological response and high coastal urbanization.

Furthermore, the operational exploitation of our results should be oriented toward monetary damage analysis to prioritize investments. Our simulations provide the necessary hydraulic foundation to evaluate the mitigation impact of Nature-Based Solutions (NBS)—such as the creation of flood expansion zones or marsh restoration—thereby demonstrating the long-term economic viability and sustainability of these solutions over traditional costly infrastructure.

5. Conclusions

This study successfully combined hydrological and hydraulic modeling to assess flood hazards and risks in the Canche and Liane catchments, utilizing HEC-HMS and HEC-RAS 6.6. The hydrological modeling provided robust flow hydrographs for multiple return periods, while the hydraulic modeling—through 1D, 2D, and combined 1D/2D simulations—offered detailed insights into floodplain dynamics, overbank flows, and flood wave propagation.

The results clearly identified the upper sectors of the Canche catchment as highly vulnerable areas, with the city of Canche facing significant flood risks, especially during extreme events where the convergence of hydraulic hazards and urban exposure creates critical conditions for populations, infrastructure, and socio-economic activities.

The flood risk maps, developed by applying the Australian Combined Hazard-Vulnerability Thresholds Classification approach [21], provided a spatially explicit understanding of the most exposed areas, thereby enabling prioritization of mitigation strategies.

Beyond these findings, the outcomes of this research highlight the necessity to advance toward long-term flood risk management planning. It is recommended that the results of this study be utilized to:

1) Develop and implement early warning systems and emergency response plans that are tailored to the most vulnerable areas, enhancing community preparedness and reducing potential flood damage.

2) Update land use and urban development plans, ensuring they account for current flood risk zones and integrate projections of climate change impacts, such

as increased rainfall intensity, sea level rise, and changes in runoff patterns.

3) Establish a dynamic flood risk management framework, which involves regular updates of flood hazard and risk maps, continuous monitoring of hydrometeorological data, and incorporation of new scenarios reflecting socio-economic and environmental changes.

This integrated approach would contribute to building more resilient territories, supporting sustainable development, and ensuring adaptive flood risk governance in the Canche and Liane basins.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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