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Physics-based Two-Dimensional Hydrodynamic Model of Riverine Flood Disasters Across Costal Cities

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Flood disasters are increasing in frequency and intensity worldwide due to climate change and sea-level rise. Meanwhile, rapid urbanization is concentrating populations, assets, and critical infrastructure systems within cities, amplifying their vulnerability to flood impacts. In this context, it is crucial to develop a principled understanding of the real-time evolution of flood-induced disruption in urban environments, to enable a robust risk assessment and informed decision-making on the emergency response. However, most existing studies rely on statistical indicators — particularly maximum water depth derived from scenario-based return-period analyses — which cannot capture the time-varying hydrodynamics of flood events, including the spatiotemporal variations in flow depth and velocity. To address this challenge, this study develops a physics-based modelling framework capable of tracking the hydrodynamics of riverine flooding in complex urban settings. The framework employs a two-dimensional hydrodynamic model that integrates in-channel flow conveyance, overbank inundation, and floodplain propagation. Its applicability is demonstrated through a case study of Cardiff, a coastal city in South Wales, as one of the most flood-prone areas in the UK. The model is first validated against Storm Claudia in 2025, which caused moderate flood-related disruption across the city. The simulated hydrodynamic behaviour shows strong agreement with the recorded observations, revealing the framework's ability to reproduce the event's temporal progression. The framework is then applied to Storm Dennis in 2020 — that triggered the most severe flood-related disruption in Cardiff since 1979 — to examine its performance under extreme conditions. The results demonstrate that the proposed framework enables nuanced, time-resolved modelling of flood dynamics, thereby establishing a robust foundation for the risk governance of urban communities imperilled by riverine flood disasters.
Keywords: Riverine flooding, Two-dimensional hydrodynamic model, Urban community, Flood risk.

1. Introduction

Climate change and sea-level rise are catalyzing flood disasters that are increasing in both the frequency and intensity worldwide. As manifested by the in-situ observations, critical infrastructure systems (CISs), which serve as the backbone of contemporary urban communities (Thacker et al. 2019), tend to sustain substantial functionality losses under major flood disasters, across the spectrum of wealth. Consequently, significant physical, economic and human losses have been triggered, across those communities affected (Koks et al. 2022, Guo et al. 2023, Fekete et al. 2025). Furthermore, rapid urbanization concentrates populations, assets, and CISs within cities, amplifying their vulnerability to flood impacts in the coming decades, particularly in the Global South (Zhang et al. 2025).

Against this backdrop, it is imperative to develop a principled understanding of the real-time evolution of flood-induced disruption in urban environments, to enable a robust risk assessment and informed decision-making on the through-flood emergency responses. So far, comprehensive researches have been undertaken to assess flood risk of the integrated CIS-urban communities (Yu et al. 2020, He et al. 2024, Alabbad and Demir 2025, Wassmer et al. 2025). Despite the insights generated, majority of these researches rely on statistical indicators—particularly the maximum water depth derived from scenario-based return-period analyses. While such indicators are relevant to the risk assessment under changing flood scenarios, they are insufficient to capture the time-varying hydrodynamics of future flood events, especially, against the backdrop of climate change. In light of the inherent scarcity of the granular record of real-world flood disasters, these indicators, obtained from the previous events, would not be capable of incorporating the non-stationary nature of extreme climate events in the coming decades, leading to an underestimation on the losses and risks. Furthermore, as a dynamic event, apart from the maximum water depth, other factors, *e.g.*, the duration and flow velocity will also play a crucial role, with respect to the disruption triggered by flood disasters.

To address this challenge, this study proposes a physics-based modelling framework that tracks the spatiotemporal hydrodynamics of flood disasters across urban communities. To that end, a two-dimensional hydrodynamic model is developed, which integrates in-channel flow conveyance, overbank inundation, and floodplain propagation. Notably, this study focuses upon the riverine flooding, as the most common and damaging scenario, in complex urban settings (Dottori et al. 2018). Its applicability is demonstrated through a case study of Cardiff, a coastal city in South Wales, as one of the most flood-prone areas throughout the whole UK. The model is first validated against Storm Claudia in 2025, which led to a moderate disruption across the city. The simulated hydrodynamic behaviour shows strong agreement with the recorded observations, demonstrating the framework's ability to replicate the event's temporal progression. The framework is then applied to Storm Dennis in 2020 — that triggered the most devastating flood-related disruption in Cardiff since 1979 (Natural Resources Wales 2023) — to examine its performance under high-stakes scenarios. The results demonstrate that the proposed framework enables nuanced, time-resolved modelling of flood dynamics, thereby establishing a robust foundation for the risk governance of urban communities imperilled by riverine flood disasters

The remainder of this paper is organized as follows. Section 2 introduces the modelling framework. Section 3 presents the outcome of the case study. Section 4 draws the main conclusions, in the end.

2. Methodology

To assess the systemic vulnerability of contemporary urban communities, this study develops a physics-based hydrodynamic simulation framework. The framework bridges the gap between physical flood modelling and community-wide risk mapping, by translating spatiotemporal hydraulic outputs into actionable disaster risk indicators. The hydrodynamic simulation is run in HEC-RAS (6.x), a widely validated numerical engine capable of capturing complex overbank propagation across urban surfaces.

2.1. *Domain parameterization and surface roughness*

Urban environments exhibit highly complex configurations comprising building clusters and intertwined CIS networks (Batty 2012, Sun 2017). To capture how this micro-topography constrains and reshapes flood pathways, a high-resolution Digital Elevation Model (DEM) derived from airborne Light Detection and Ranging (LiDAR) serves as the primary terrain layer.

Meanwhile, hydraulic shear resistance across the domain is governed by Manning's roughness coefficient. To account for the contrasting drag mechanisms of the natural river channel and the built environment, the domain is partitioned into two main friction zones:

- **River channel roughness (n_r):** Assigned a baseline value to account for the alluvial channel friction, bedform irregularities, and minor bank vegetation;
- **Urban floodplain Roughness (n_f):** Assigned a macro-roughness value to macroscopically simulate the retarding effects of street furniture, peripheral vegetation, and varied land-use characteristics.

2.2. *Hydrological forcing and boundary conditions*

In this study, the model is driven by distinct upstream and downstream boundary conditions that replicate a severe riverine flood event.

2.2.1. *Upstream boundary*

The upstream forcing condition is prescribed via a continuous flow hydrograph. As extreme riverine inundation within British catchments often exhibits multi-day durations (Najibi and Devineni 2018), a continuous discharge hydrograph spanning a 3-day window is utilized.

This setup ensures a physically consistent representation of the total flood wave volume and peak discharge arrival times.

2.2.2. *Downstream boundary*

In contemporary coastal and estuarine urban communities, riverine outlets are frequently modified by civil infrastructure — such as tidal barrages, storm surge barriers, or regulated sluice complexes — to manage water levels and mitigate tidal ingress. To ensure the framework accurately captures the resulting backwater hydrodynamics and hydrodynamic choking during extreme fluvial forcing, the downstream boundary is modelled as an idealized broad-crested weir, in this study.

Quantitatively, the relationship between the outflow discharge (*Q*) passing through the downstream boundary and the hydraulic head (*H*) upstream of the infrastructure crest is governed by the classical weir flow model (Hager and Schwalt 1994), as shown in Eq. (1):

$$Q = B\,C\,\sqrt{2g}\,H^{3/2} \tag{1}$$

where *B* denotes the effective structural width of the operational outflow gates, *C* is the non-dimensional discharge coefficient accounting for localized structural energy losses, and *g* refers to the gravitational acceleration.

Accordingly, given *Q(t)* at any time point *t*, *H(t)* can be obtained following Eq. (2):

$$\mathrm{H(t)} = \left(\frac{Q(t)}{BC\sqrt{2g}}\right)^{\frac{2}{3}} \tag{2}$$

The dynamic downstream water surface elevation, denoted as Stage (t), is explicitly tracked relative to the fixed structural crest elevation (Z_c) of the impounding infrastructure, and can be determined following Eq. (3):

$$\mathrm{Stage(t)} = z_c + H(\mathrm{t}) \tag{3}$$

By integrating this stage–discharge rating relationship at the domain exit, the numerical framework explicitly accounts for the physical backwater constraints imposed by macro-scale downstream infrastructure. This prevents artificial numerical drawdown and ensures that upstream overbank flooding and subsequent water depths across the urban floodplain remain physically representative of heavily managed urban catchments.

2.3. *Numerical Setup and Discretization*

The computational domain is discretized into a 2D sub-grid mesh. To balance computational efficiency with localized granularity, an adaptive meshing strategy is deployed. The sprawling urban floodplain is discretized using a uniform grid size, whereas the primary river channel is constrained by directional breaklines along the banks. These breaklines force cell alignment parallel to the channel margins, preserving bank geometry and preventing premature artificial overbank spilling. The internal channel mesh is locally refined to track steep spatial gradients in the water surface profile.

Hydrodynamic routing is executed using the 2D Diffusion Wave (DW) approximation of the Shallow Water Equations (SWE). The DW solver simplifies the full momentum equations by neglecting local and convective acceleration (inertial terms), assuming that gravitational forces are balanced primarily by bottom friction. In light of the flat, low-gradient morphology of the coastal floodplain and the slowly rising nature of the fluvial hydrograph, the omission of these inertial acceleration terms remains physically appropriate and computationally robust for macro-scale inundation extent mapping.

Temporal discretization is fixed at a constant time step, denoted as Δ_t and selected to maintain numerical stability. To mitigate initial numerical shock stemming from dry computational cells, a warm-up period, denoted as T_w, is executed under baseflow conditions, establishing a stable, physically consistent initial wetting state across the river network prior to hydrograph routing.

2.4. *Model outputs*

In this study, both water depth and flow velocity were tracked throughout the hydrodynamic simulations. While water depth is the primary focus of the research around flood risks, flow velocity is often overlooked despite its critical role in driving flood-induced disruption in urban environments. Specifically, water depth characterizes the localized severity of static inundation, whereas flow velocity measures the kinetic intensity and real-time propagation of floodwaters. When combined together, these two hydrodynamic responses enable a more nuanced and physically-grounded assessment of flood impacts, laying a solid foundation for the risk analysis and governance within urban communities.

3. Case study

The model developed in Section 2 is employed to simulate the hydrodynamic response of the urban area of Cardiff City, in the UK, as a real-world testbed. The simulated outcome from the newly-developed model has been validated against the recorded data, at first. A scenario-based study has been undertaken thereafter, under Storm Dennis, a real-world extreme climate event, in 2020.

3.1. *Configuration of the testbed*

The urban area of Cardiff, situated within one of the most flood-prone regions of the UK, is adopted as the testbed of this study (Bates et al. 2023). As illustrated in Fig. 1, the delineated area — outlined by the red dashed boundary — encompasses the principal urbanised zone of the city, covering approximately 107 km² and hosting a population of 341,506. This represents roughly 89% of Cardiff's total population, thereby capturing the dominant concentration of exposure and vulnerability relevant to this research.

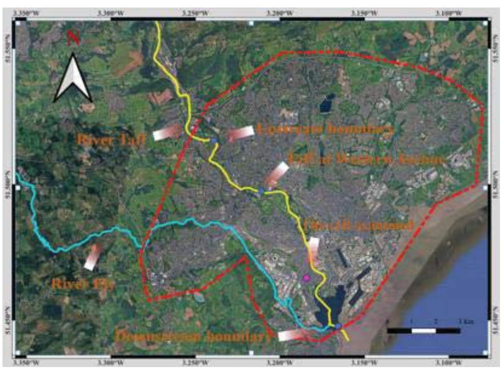


Fig. 1. The testbed community.

Flood risk in Cardiff is shaped predominantly by the **River Taff** and the **River Ely**, the two major river systems traversing the city. As highlighted in Fig. 1, extensive high-risk zones are distributed along the River Taff corridor and across the downstream reaches of the River Ely (Natural Resources Wales 2026).

To construct a 2D hydrodynamic model of the area, a LiDAR data of DEM with a spatial resolution of 2 m × 2 m is used as the terrain basis, in this case study. Pursuant to the adaptive meshing strategy outlined in Section 2.3, the urban floodplain mesh was assigned a uniform cell size of 10 m × 10 m, while the in-channel mesh was locally refined along the breaklines to 5 m × 5 m, to capture localized channel variations. Accordingly, the whole model consisted of a total of 398,652 two-dimensional computational cells, with cell areas ranging from 8.19 m² to 246.64 m².

Regarding the main river channel and the urban floodplain area, the Manning's roughness coefficients, *i.e.*, n_r and n_f, are set as 0.02 and 0.06, respectively, to account for the difference between their flow resistances. Under any given flood scenario, the time step of the hydrodynamic simulation, *i.e.*, Δ_t, and the corresponding output interval is set to be 10s and 15 min, respectively. Besides, the T_w that denotes the duration of the warm-up run is 30 h, to ensure a stabilisation toward a quasi-steady state, and ultimately, to minimize the influence of the initial condition on the hydrodynamic responses of the area.

As mentioned in Section 2.2 and illustrated in Fig. 1, the downstream outflow section is modelled as an idealised broad-crested weir. Quantitatively, the parameters, *i.e.*, B, C, and Z_c that are included in the Eqs. (1) and (3), are set as 60 m, 1.5, and 4.5 m, respectively. Based on these parameters, a physically-consistent stage–discharge relationship is established at the downstream boundary, ensuring the numerical stability of the model.

3.2. *Model validation*

To evaluate the predictive accuracy of the physics-based framework developed in Section 2, the model was deployed to simulate the hydrodynamic response of the River Taff in Cardiff, Wales. The framework was validated using high-resolution hydrological data collected during Storm Claudia (November 2025), a convective meteorological event that caused moderate, widespread disruption across the Cardiff municipality (BBC 2025).

The continuous discharge time-history recorded between November 11 and November 14, 2025, at the Upper Boat Bridge gauging station served as the upstream hydrological forcing boundary condition, as shown in Fig. 1. To evaluate model performance, the simulated stage response was extracted and compared against empirical water-level observations at the Western Avenue gauging station, as the final down-gradient, level-only monitoring node within the study reach (Fig. 1).

A spatial discrepancy exists between the physical location of the upstream monitoring station at Upper Boat Bridge and the boundary of the numerical model, as highlighted in Fig. 1. This spatial offset inherently introduces a phase error or temporal misalignment. To mitigate this phase discrepancy and preserve temporal consistency between the empirical observations and the numerical simulation, a localized time-lag correction was implemented. The travel time between the physical gauging asset and the computational boundary was parameterized based on the mean cross-sectional channel velocity and reach length. The observed upstream hydrograph was subsequently phase-shifted. This boundary condition adjustment ensures tight synchronization of the volumetric flux and hydraulic forcing within the numerical engine, maintaining physical consistency.

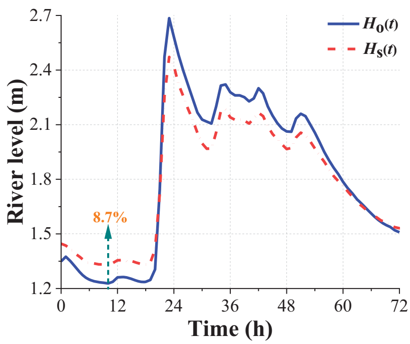


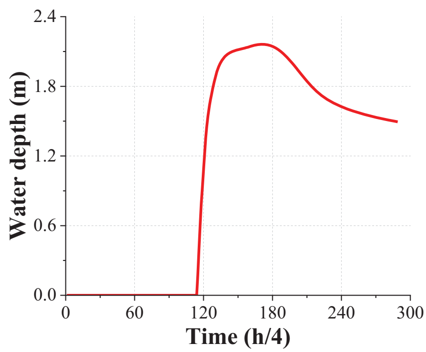
Fig. 2. Time-varying river level under Storm Claudia.

The empirical and simulated river level time-histories, denoted as $H_o(t)$ and $H_s(t)$, respectively, are compared across the 3-day simulation window in Fig. 2. The simulated stage hydrograph exhibits strong morphological alignment with the observed empirical trend throughout the entire duration of the storm event. Both the observed and simulated profiles reach their respective peak hydraulic stages at approximately t = 24 hours after the initialization. At the peak of the flood wave, the observed depth of 2.69 m vs. the simulated depth of 2.47 m yields a localized error of 7.9%. Crucially, the maximum structural discrepancy across the entire transient simulation remains bounded below 10%. The peak error is 8.7% and occurs during the initial phase of the event, a period characterized by shallow flows where low-water levels are highly sensitive to small absolute variations, as shown in Fig. 2. The low error bounds and precise phase matching demonstrate that the framework is capable of capturing the transient hydrodynamic behaviour of riverine flooding.

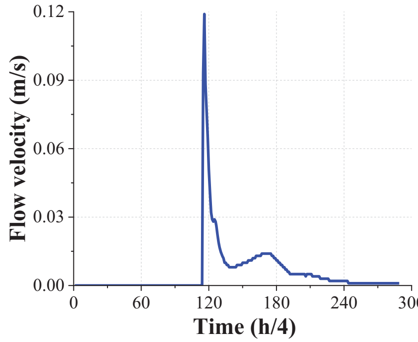
3.3. *Hydrodynamic response under Storm Dennis*

Based on the modelling framework developed in Section 2 and validated in Section 3.2, the hydrodynamic behaviour of the testbed was examined under Storm Dennis (February 2020). This event represents one of the most catastrophic fluvial floods recorded in South Wales since 1979 (Natural Resources Wales 2020), providing a high-stakes scenario for urban risk analysis. Time-varying water depth and flow velocity profiles were extracted from a densely populated urban neighbourhood situated near the confluence of the River Taff and River Ely (demarcated as a focal area in Fig. 1).

The transient simulation encompassed a 72-hour period, exclusive of the initial baseline warm-up phase. As illustrated in Fig. 3(a) and Fig. 3(b), both the water depth and flow velocity initiate a sharp, synchronized escalation at approximately t = 28.5 hours post-onset.



(a) Water depth



(b) Flow velocity

Fig. 3. Time-varying hydrodynamic response.

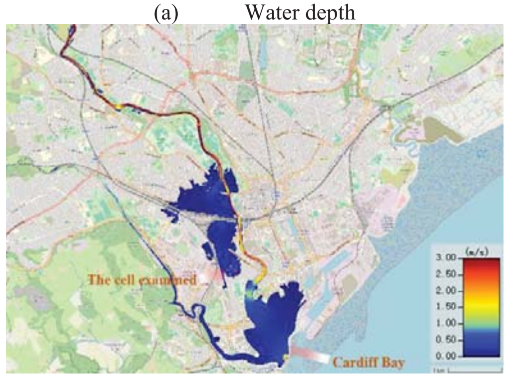
Nevertheless, the localized hydrodynamic trajectories diverge significantly thereafter:

- **Water Depth Evolution:** From t=28.5 hours, the inundation depth increases quasi-linearly, surpassing 2.0 m within a 5-hour window. Beyond this stage, the accumulation rate attenuates. After an additional 9 hours of gradual linear growth, the water depth peaks at 2.16 m at t = 43 hours before receding monotonically to a final depth of 1.49 m by the conclusion of the 72-hour timeframe, as shown in Fig. 3(a);
- **Flow Velocity Evolution:** Conversely, the localized flow velocity exhibits a highly transient, impulsive behaviour. Following the inflection point, the velocity rapidly climbs to its peak value of 0.12 m/s within just 30 minutes, immediately followed by a steep decay. By t = 72 hours, the local velocity approaches a near-static condition, as highlighted in Fig. 3(b).

Spatial distributions of the maximum water depth and flow velocity across the broader municipal domain are illustrated via the contour plots in Fig. 4(a) and Fig. 4(b), respectively. The extreme forcing yields widespread inundation across the urban core. Spatial analysis reveals a pronounced geometric divergence between the two hydrodynamic parameters. The majority of the low-lying delta area between the lower reaches of the River Taff and River Ely is characterized by extensive, deep water accumulation. In contrast, elevated flow velocities are primarily constrained along the left bank of the main River Taff channel, dictating localized zones of high kinetic energy.

Ultimately, these findings underscore the highly complex spatiotemporal evolution of hydrodynamics within contemporary urban environments during major riverine events. Crucially, the observed temporal and spatial asynchrony between peak water depth and maximum flow velocity highlights that flood-induced disruptions are highly heterogeneous, shifting dynamically in real-time across the affected community.

(a) Water depth



(b) Flow velocity

Fig. 4. Disruption across the whole testbed.

5. Conclusions

This study presented a physics-based modelling framework designed to track hydrodynamics of riverine flooding across contemporary urban environments. The framework utilizes a high-resolution, two-dimensional hydrodynamic engine that integrates in-channel flow conveyance, overbank inundation, and urban floodplain propagation. The applicability and predictive performance of the model were evaluated using Cardiff, South Wales—a highly vulnerable coastal municipality.

The framework was first validated against Storm Claudia (2025), a moderate flood event, demonstrating strong alignment with empirical stage observations. Subsequently, the model was deployed to simulate the catastrophic impacts of Storm Dennis (2020), the most severe fluvial flood event in the region since 1979, to evaluate its robustness under extreme, high-stakes forcing conditions. The primary findings of this research are summarized as follows:

- **High-Fidelity Dynamic Simulation:** The physics-based framework enables high-fidelity, nuanced modelling of the spatiotemporal evolution of flood waves across complex, highly heterogeneous urban surfaces;
- **Hydrodynamic Asynchrony:** A pronounced spatial and temporal asynchrony was observed between time-varying water depths and flow velocities within the built environment;
- **Implications for Risk Mapping:** The localized decoupling of depth and velocity highlights the limitations of traditional, static flood indicators. Consequently, a multi-parameter, physics-based vulnerability assessment approach needs to be adopted to capture the real-time, compound impacts of these distinct hydrodynamic properties on urban disruptions.

In summary, this study establishes a robust, physically-grounded foundation for real-time risk assessment. The proposed framework provides actionable insights to support informed emergency response operations, proactive through-flood decision-making, and long-term climate resilience governance in vulnerable urban communities worldwide.

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