An integrated hydrological connectivity framework for urban stormwater flooding management at catchment scale

Un cadre intégré de connectivité hydrologique pour la gestion des inondations pluviales urbaines à l’échelle du bassin versant

Yuxuan Yao, Guangtao Fu, James Webber
Centre for Water Systems, Department of Engineering, University of Exeter
yy546@exeter.ac.uk, G.Fu@exeter.ac.uk, J.Webber2@exeter.ac.uk

RÉSUMÉ

Les inondations pluviales urbaines émergent de l’activation, lors des événements, d’écoulements connectés à travers des paysages hétérogènes. Pourtant, la connectivité hydrologique (CH) est encore souvent gérée de manière implicite plutôt que considérée comme une propriété explicite gouvernant la réponse aux inondations, ce qui affaiblit la compréhension de la façon dont le ruissellement local se transforme en aléas systémiques et limite l’alignement des interventions locales avec les processus à l’échelle du bassin versant. Nous développons et testons un cadre diagnostique fondé sur l’IHC pour les inondations pluviales urbaines et proposons une extension de théorie des graphes afin de traduire les motifs de connectivité en priorités opérationnelles de réseau. Nous produisons des cartes IHC spécifiques aux événements pour des pluies de projet de périodes de retour 10, 30 et 100 ans, et relions des caractéristiques IHC multi-échelles aux inondations simulées à l’aide de XGBoost et d’outils d’interprétation du modèle. Les résultats indiquent que les variables IHC améliorent nettement l’explication de l’organisation spatiale des inondations et révèlent une transition, conditionnée par la profondeur, vers des inondations dangereuses de plus en plus limitées par la capacité de transfert, liées à des apports dynamisés par la pente interagissant avec des corridors de forte connectivité et des goulets d’étranglement. L’extension par graphes proposée devrait permettre d’identifier des nœuds et liens critiques pour le système et de soutenir la priorisation des interventions fondée sur l’effet de levier de connectivité.

ABSTRACT

Urban stormwater flooding emerges from the event-driven activation of connected water flow across heterogeneous landscapes. Yet hydrological connectivity (HC) is still commonly managed implicitly rather than treated as an explicit governing property of flood response, weakening understanding of how local runoff escalates into systemic hazards and limiting alignment of local interventions with catchment-scale processes. We develop and test an IHC-based diagnostic framework for urban stormwater flooding and propose a graph-theoretic extension to translate connectivity patterns into actionable network priorities. We derive event-specific IHC maps for 10-, 30-, and 100-year design storms and relate multi-scale IHC features to simulated inundation using XGBoost with model-interpretation tools. Results indicate that IHC features substantially improve explanation of flood spatial organisation and reveal a depth-conditioned transition toward conveyance-limited hazardous flooding linked to slope-energised inflows interacting with high-connectivity corridors and bottlenecks. The proposed graph extension is expected to identify system-critical nodes and links and support intervention prioritisation based on connectivity leverage.

KEYWORDS

graph and network analysis, hydrological connectivity, Index of Hydrological Connectivity, stormwater flooding, urban catchment management

1 INTRODUCTION

Urban stormwater flooding is an emergent phenomenon driven by the cascading transfer of runoff across the entire catchment. Although cities have invested heavily in both grey drainage upgrades and green infrastructure, catchment flood protection targets often fall short of expectations (Tran et al., 2024). Diagnosing how local runoff escalates into systemic inundation and identifying where interventions can most effectively disrupt flood propagation, remains a persistent challenge. A primary driver of this failure is a reductionist, asset-centric paradigm that optimizes stormwater infrastructure component by component, treating it as an inventory of isolated assets rather than an interconnected network (Golden & Hoghooghi, 2018). System evaluation also relies heavily on aggregated end-point metrics (e.g., outlet hydrographs or total inundated area), which further obscures the internal routing pattern that governs flood behaviour (Niazi et al., 2017). As a result, it remains difficult to link fine-scale pathway activation to system-wide flood response and to align local actions with the flow processes that dominate risk at larger spatial scales.

The concept of hydrological connectivity (HC) offers a systems framework that treats the pattern of water-mediated links among heterogeneous landscape as an explicit catchment property (Bracken et al., 2013). The concept has progressed to operational quantitative approaches. For example, Index of hydrological connectivity provides a catchment-scale quantification of the potential magnitude of storm driven water flow connectivity (Zanandrea et al., 2021). Furthermore, graph-based approaches have gained prominence for analysing connectivity from a holistic perspective, enabling the quantification of global topological properties and the identification of critical locations for system-wide impacts (Tiwari et al., 2024).

While the HC framework has been widely applied in natural catchments to elucidate non-linear runoff responses, such as river flooding, its application in urban catchments remains nascent. Extending HC framework to urban stormwater flooding raises several challenges. For example, a central challenge in the application of IHC is mismatch in spatial scales. Flood triggering connectivity is organised at neighbourhood extents, whereas IHC is computed at pixel resolution, requiring process-relevant spatial aggregation and descriptors for which consensus is still emerging (Heckmann et al., 2018). Similarly, for graph-based method, defining edges and nodes that can represent dynamic development of hydrological connectivity presents conceptual difficulties.

In this study, we develop and test an integrated hydrological connectivity framework that couples event-specific IHC mapping with graph-based diagnostics to explain catchment-scale stormwater flood emergence. Using multi-scale IHC neighbourhood features and XGBoost with model-interpretation tools, we relate connectivity patterns to simulated inundation across 10-, 30-, and 100-year design storms. In parallel, we translate IHC-informed surface pathways into directed, weighted graphs to identify system-critical corridors, junctions, and potential bottlenecks. Together, these analyses move beyond static indicators by capturing non-linear interactions between rainfall intensity, urban heterogeneity, and pathway activation. By comparing connectivity features across spatial supports, we assess scale sensitivity and identify shifts in dominant controls consistent with transitions from storage- to conveyance-limited flood behaviour. We demonstrate the framework in the Exeter catchment (UK) and show how it can support strategic targeting of interventions to disrupt hazardous flow pathways.

2 METHODOLOGY

The framework was developed and tested in Exeter, UK, within an ~84 km² catchment representative of mixed urban–rural morphology and stormwater flood pressure. The research integrates two distinct phases to bridge physical process understanding with strategic application.

2.1 Phase 1

We explored the relationship between IHC and flood patterns using an interpretable machine learning model (XGBoost). First, we derived flood-extent maps for 1, 5, and 15 cm depth thresholds under 10-, 30-, and 100-year design storms using a hydrodynamic model (InfoWorks ICM). We then calculated event-conditioned IHC maps (Figure 1) and generated multiscale explanatory variables using sliding-window aggregation (nine sized from 3 to 260) to capture neighbourhood context and scale sensitivity, summarised by mean, variance, P10, and P90. Next, we built tiered XGBoost models that compared a baseline using traditional explanatory variables excluding IHC with models that added raw IHC and then multiscale IHC features to quantify the incremental explanatory contribution of connectivity. We interpreted model results using SHAP and Partial dependence plots (PDP) to identify dominant IHC metrics and the characteristic spatial support of connectivity controls on flood patterns.

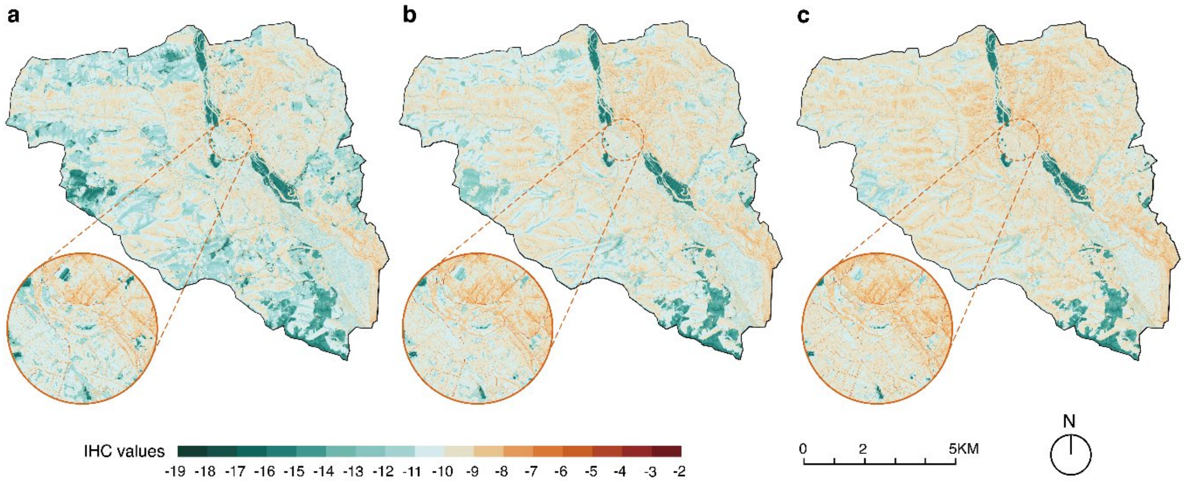


Figure 1 IHC map for design storm events in study area. a, 10-year. b, 30-year. c, 100-year.

2.2 Phase 2

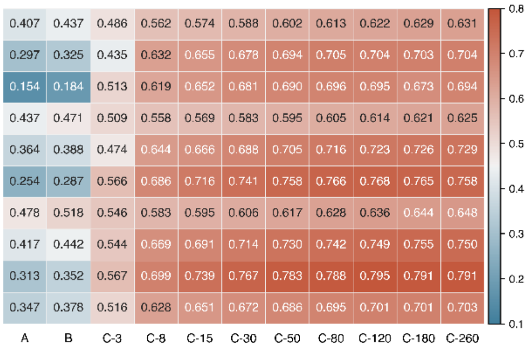
A separate directed, weighted graph will be constructed for each design storm to enable comparison of network structure across scenarios. Directed edge weights will be assigned based on IHC values to map the strength and directionality of surface hydrological connectivity into a network representation. This event specific graph set preserves fine scale HC patterns. Graph theory-based metrics will be used to quantify node and link criticality to support identification of priority locations.

3 RESULTS, DISCUSSION AND FUTURE WORK

3.1 Phase 1: The relationship between IHC and spatial patterns of stormwater flooding

3.1.1 *Incremental value of IHC and characteristic spatial support*

To isolate the explanatory contribution of IHC, we compared three-tiered model configurations: a baseline using traditional topographic variables (Model A), models adding raw IHC (Model B), and models integrating spatially aggregated IHC features (Model C). Results show that spatial aggregation provides the primary source of explanatory gain for XGBoost (Figure 2) While adding raw IHC (Model B) offers only marginal improvements, the aggregated features in Model C consistently significant outperform the baseline, particularly for hazardous flooding. For the 100-year, 15 cm scenario, Model C increased the Critical Success Index (CSI) by 154% relative to Model A (from 0.313 to 0.795).



A	B	C-3	C-8	C-15	C-30	C-50	C-80	C-120	C-180	C-260
0.407	0.437	0.486	0.562	0.574	0.588	0.602	0.613	0.622	0.629	0.631
0.297	0.325	0.435	0.632	0.655	0.678	0.694	0.705	0.704	0.703	0.704
0.154	0.184	0.513	0.619	0.652	0.681	0.690	0.696	0.695	0.673	0.694
0.437	0.471	0.509	0.558	0.569	0.583	0.595	0.605	0.614	0.621	0.625
0.364	0.388	0.474	0.644	0.666	0.688	0.705	0.716	0.723	0.726	0.729
0.254	0.287	0.566	0.686	0.716	0.741	0.758	0.766	0.768	0.765	0.758
0.478	0.518	0.546	0.583	0.595	0.606	0.617	0.628	0.636	0.644	0.648
0.417	0.442	0.544	0.669	0.691	0.714	0.730	0.742	0.749	0.755	0.750
0.313	0.352	0.567	0.699	0.739	0.767	0.783	0.788	0.795	0.791	0.791
0.347	0.378	0.516	0.628	0.651	0.672	0.686	0.695	0.701	0.701	0.703

Figure 2 CSI score across all scenarios and configurations.

The F1 score results confirm a clear window size effect (Figure 3). XGBoost Performance rises rapidly at small supports, then approaches diminishing returns and reaches a broad plateau beyond the 80-window size, with performance peaking around C-120. This indicates that intermediate neighbourhood context best balances information and local heterogeneity.

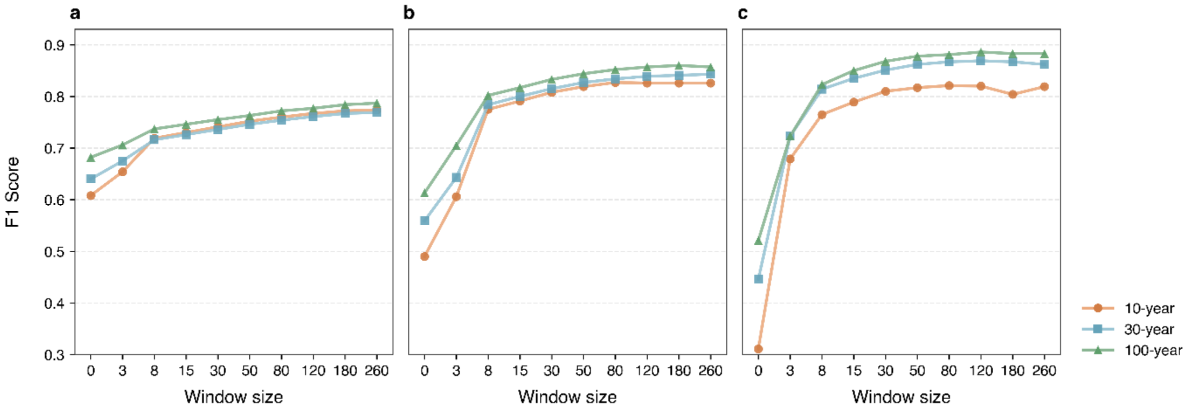


Figure 3 F1 score as a function of aggregation window size. Panels are stratified by flood depth: a 1 cm, b 5 cm, and c 15 cm. The plots show the F1 Score for Model C configurations across a range of window sizes, compared to the raw IHC model (Model B, shown at window size 0).

3.1.2 From storage to conveyance depth dependent connectivity regimes

PDP analysis shows a fundamental regime shift in flood drivers that is governed primarily by inundation depth. Nuisance flooding (1cm depth) is storage driven and responds most strongly to neighbourhood heterogeneity and local retention structure captured by IHC Variance and P10 (Figure 4a, 4c). Under these conditions, the landscape behaves as a mosaic of partially disconnected sinks, where micro-topography traps runoff locally. As flooding deepens to hazardous levels (e.g., 15 cm), the influence of local variance diminishes, while the sensitivity to efficient flow corridors (IHC P90) remains dominant (Figure 4b). This signals a transition to a conveyance-limited logic, where flood extent is controlled by the network's capacity to evacuate water.

The 2D PDP surfaces reinforce this interpretation by showing that steep slopes amplify hazard when they deliver inflows into low IHC P10 bottlenecks or highly variable neighbourhood connectivity, whereas high IHC P90 rapidly collapses predicted hazard and reduces sensitivity to slope or curvature (Figure 5). Together, these PDP results support a conveyance limited mechanism in which hazardous flooding emerges when slope energised inflow interacts with corridor and bottleneck structure rather than with additional local storage demand

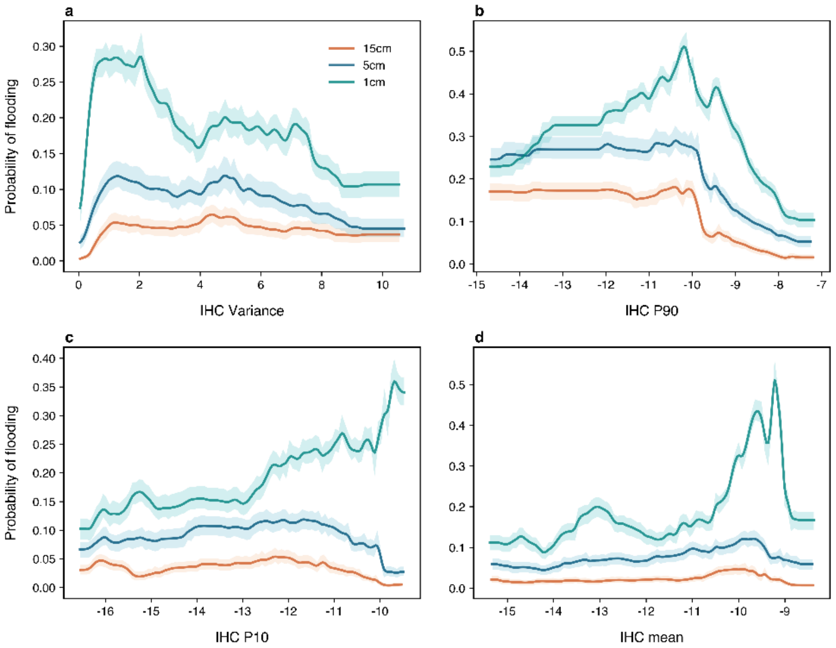


Figure 4 PDPs for the four aggregated IHC features under increasing inundation depth (Model C-120, 30-year storm). Lines indicate the marginal probability of a pixel exceeding 1 cm, 5 cm, and 15 cm water depths for the 30-year design storm. Ribbons indicate 95 % bootstrap confidence intervals.

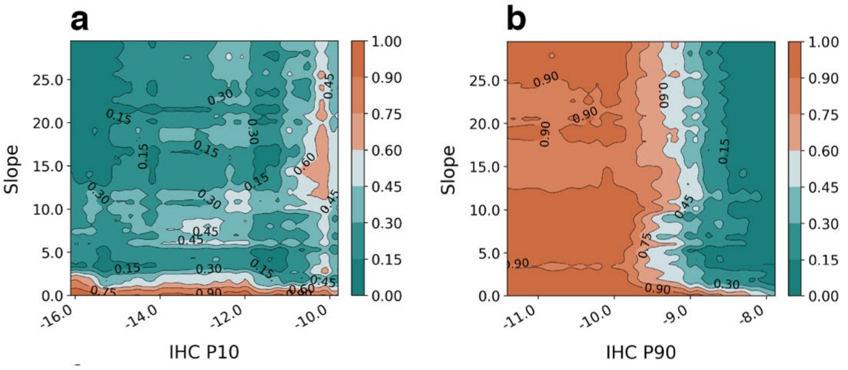


Figure 5 2D-PDP of hazardous flooding at 15 cm for the 30-year storm. The six panels show the joint marginal effects of the most influential IHC feature pairs. Warmer colours indicate higher predicted flood probability.

3.2 Phase 2: Proposed Exploration – Strategic Network Diagnostics Based on IHC

This proposed graph extension aims to inform connectivity-based intervention prioritisation. The analysis is expected to identify nodes and links with high connectivity leverage, defined as locations where local defined as locations where local actions may deliver larger downstream or network wide benefits. Cross scenario comparison may distinguish storm robust critical elements from event sensitive ones, clarifying which corridors and bottlenecks repeatedly govern hazardous organisation. The anticipated contribution is a defensible prioritisation logic that targets critical connection pathways rather than relying on opportunistic implementation.

4 CONCLUSION

This study demonstrates that event-specific IHC, analysed across multiple spatial supports, can substantially improve explanation of urban flood spatial organisation and reveal a shift toward conveyance-limited hazardous flooding under deeper conditions. By developing an IHC-informed graph extension, we provide a pathway to translate connectivity patterns into system-critical nodes, links, and intervention priorities. These advances support more strategic stormwater flood management, enabling alignment of local interventions with management goals at catchment scale.

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