



Review Article: Compound Flooding in Coastal and Estuarine Catchments: Modelling, Management, and Climate Adaptation Insights from Cork Harbour

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Abstract

Compound flooding (CoMF) has emerged as a critical natural hazard for coastal and estuarine regions, where interacting
10 fluvial, pluvial, groundwater, tidal, and storm surge processes generate non-linear amplification effects that challenge
conventional single driver flood risk assessments. Yet, despite major advances in compound flood science, integrated literature
reviews that link multivariate hazard dynamics, modelling approaches, risk management, and climate adaptation strategies
remain limited. This systematic review synthesises three decades of research on CoMF in Cork Harbour and Catchment (CHC),
a highly dynamic coastal-estuarine system increasingly exposed to climate change. Following PRISMA guidelines, 503
15 documents were screened across Web of Science, Scopus, Google Scholar, and grey literature sources, identifying 59 peer-
reviewed articles and 28 technical reports and policy documents published between 1991 and 2025.

This review provides two key contributions of international importance. First, it positions CHC as a potential national reference
site and globally relevant compound flood model system, demonstrating how climate driven interactions between extreme
rainfall, river discharge, storm surge, tides, and Sea-Level Rise (SLR) generate non-linear amplification effects. Results reveal
20 that while fluvial processes currently dominate with a 30% increase in future flood inundation, projected SLR and surge
intensification could amplify coastal inundation by up to 400%, surpassing fluvial contributions and shifting the dominant
contribution towards coastal mechanisms. Second, it offers a transferable methodological scheme, showcasing best practice
integration of multi-scale hydrodynamic modelling, multivariate statistical dependence analysis, and emerging physics
informed AI tools capable of improving real time forecasting. Advances in high-resolution hydrodynamic modelling and
25 multivariate statistical frameworks have improved simulation fidelity, yet critical gaps persist—particularly in probabilistic
modelling, artificial intelligence (AI) enhanced real-time forecasting, and integration of urban drainage and socio-ecological
resilience.

We identified six priority future research directions that could assist in implementing local action and hence have transferable
international relevance: (i) probabilistic and machine-learning approaches for compound flood hazard prediction; (ii)
30 integrated modelling frameworks coupling climatic, hydrodynamic, and socio-ecological systems; (iii) continuous climate and



hydrological monitoring infrastructure; (iv) sensor networks for real-time data acquisition; (v) AI-enhanced real-time forecasting platforms and (vi) adaptive governance for climate-resilient hybrid structural and non-structural interventions. By consolidating existing knowledge and articulating clear future research priorities, this contributes a comprehensive and transferable framework for understanding, modelling, and adapting to compound flood risk in a warming world.

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Keywords: Extreme climate events; Compound Flooding; Source to sea; Coastal and fluvial interactions; Climate change impacts; Flood risk; Hydrodynamic modelling; Artificial intelligence; Machine learning; Systematic literature review

Introduction

40 Flooding is one of the most frequent and destructive natural hazards worldwide (Bubeck et al., 2017; Rentschler et al., 2022), and its impacts are projected to intensify under combined influence of climate change, increasing hydro-meteorological extremes (Arnell & Gosling, 2016; Kundzewicz et al., 2014), urbanisation, land use change, and the growing concentration of population and critical infrastructure in coastal regions. Flood affects lives, livelihoods, economies, and ecosystems at scales unmatched by many other climate-related hazards (Allaire, 2018; Green et al., 2025; Mishra et al., 2022; Rentschler et al., 45 2022). Recent global estimates indicate that 1.8 billion people (~23% of the world's population) are directly exposed to a 1-in-100-year flood event (Rentschler et al., 2022). Coastal-estuarine environments are particularly vulnerable to flooding because they form dynamic interfaces where atmospheric, hydrological, terrestrial, and marine processes interact, while climate-driven changes in these systems are increasing flood frequency and magnitude (Arnell & Gosling, 2016; Dettinger, 2011; Hirabayashi et al., 2013; Kundzewicz et al., 2014) and amplifying risks to densely populated coastal and estuarine 50 regions (Edmonds et al., 2020; Neumann et al., 2015). Conventionally, flood risk assessments have focused on riverine, coastal, or pluvial hazards in isolation, yet flooding in coastal-estuarine systems increasingly results from the interaction of multiple flood-generating processes, producing compound impacts that often exceed those expected from individual drivers alone. Increasing evidence shows that many of the most damaging flood events result from the interaction of multiple flood-generating drivers, including fluvial, pluvial, coastal, groundwater, and antecedent environmental conditions, whose temporal 55 or spatial concurrence can produce nonlinear impacts that far exceed the sum of their individual effect (Bevacqua et al., 2019; Green et al., 2025; Leonard et al., 2014; Wahl et al., 2015; Zscheischler et al., 2018). Such events, commonly referred to as compound floods, have become a major focus of contemporary natural hazard science because their impacts are often nonlinear and substantially greater than those associated with individual drivers operating independently (Eilander et al., 2023; Green et al., 2025; Hendry et al., 2019; Wahl et al., 2015). Consequently, CoMF has emerged as a critical frontier in flood-risk science, 60 challenging traditional assessment paradigms and driving the development of innovative conceptual frameworks, advanced modelling approaches, and integrated risk-management and climate adaptation strategies.



Over the past decade, CoMF has emerged as one of the fastest-growing areas of research within hydrology, coastal science, climate-risk assessment, and natural hazards studies. This growing attention reflects increasing recognition that flood hazards in coastal-estuarine systems rarely result from a single process acting in isolation; rather, they are often generated through the interaction of multiple hydrometeorological and oceanographic drivers operating across interconnected catchment and coastal (Bevacqua et al., 2019; Green et al., 2025; Hendry et al., 2019; Leonard et al., 2014; Messori et al., 2021; Wahl et al., 2015; Zscheischler et al., 2018). CoMF refers to situations in which two or more flood generating processes occur simultaneously, sequentially, or cumulatively, producing impacts that exceed those expected from individual flood driver acting independently (Bevacqua et al., 2019; Green et al., 2025; Hendry et al., 2019; Leonard et al., 2014; Wahl et al., 2015; Zscheischler et al., 2018). These interactions typically involve combinations of fluvial flooding driven by river discharge, pluvial flooding arising from intense rainfall and surface runoff, coastal flooding associated with storm surge, tides, waves, and sea-level rise (Philipp Heinrich et al., 2023a; P. Heinrich et al., 2023; Nasr et al., 2021; Wahl et al., 2015; Zscheischler et al., 2018), as well as ground water flooding linked to elevated groundwater tables (Glas et al., 2025; Green et al., 2025; Hendry et al., 2019; Seidenfaden et al., 2025; Wahl et al., 2015). The concurrence of these drivers can generate highly nonlinear responses, resulting in flood depths, extents, durations, and associated damages that substantially exceed the sum of their individual effects and frequently surpass the design capacity of conventional flood-defence and emergency-management systems (Bevacqua et al., 2019; Green et al., 2025; Hendry et al., 2019; Wahl et al., 2015).

These dynamics are particularly pronounced in low-lying coastal-estuarine environments, where strong interactions between upstream hydrological processes and downstream coastal forcing create conditions conducive to compound flooding. Extreme rainfall, high river discharges, storm surges, tidal amplification, rising sea levels, and groundwater responses frequently co-occur or closely follow one another, amplifying flood risk across both urban and rural landscapes (Bevacqua et al., 2019; Bevacqua et al., 2020; Eilander et al., 2023; Glas et al., 2025; Green et al., 2025; Harrison et al., 2022; Hendry et al., 2019; Seidenfaden et al., 2025; Wahl et al., 2015). The resulting flood impacts are often highly nonlinear, generating flood depths, extents, durations, and damages that substantially exceed those expected from individual hazards alone and frequently surpass the design capacity of conventional flood-defence and emergency-management systems (Bevacqua et al., 2019; Bevacqua et al., 2020; Green et al., 2025; Harrison et al., 2022; Hendry et al., 2019). Growing evidence further suggests that climate change is intensifying both individual flood drivers and their interdependencies, increasing the likelihood of concurrent meteorological and oceanographic extremes and thereby enhancing compound flood risk in many coastal regions worldwide (Bevacqua et al., 2019; Bevacqua et al., 2020; Eilander et al., 2023; Ganguli et al., 2020; Philipp Heinrich et al., 2023a). These emerging challenges have stimulated major advances in compound flood research, ranging from statistical dependence analyses and process-based hydrodynamic modelling to machine-learning applications, hybrid physical-statistical frameworks, and integrated climate-risk assessment approaches (Akter & Ataulloh, 2025; Eilander et al., 2023; Radfar et al., 2026; Ruan et al., 2024; Xu et al., 2023). Climate change is leading to more frequent and severe compound meteorological-oceanographic extremes, particularly across mid-latitude coastal regions (Messori et al., 2021). Such developments are particularly relevant



95 for Atlantic-facing European estuaries such as Cork Harbour, where strong fluvial-coastal interactions, tidal amplification, urban exposure, and projected sea-level rise combine to create a highly representative coastal-estuarine testbed for investigating present and future compound flood risk.

Recent review studies have synthesized many of these developments, focusing on modelling methodologies, assessment frameworks, climate-change impacts, urbanisation effects, and compound flood mechanisms in coastal and urban environments (Akter & Ataullah, 2025; Jahani et al., 2026; Ruan et al., 2024; Xu et al., 2023). Most notably, Green et al. (Green et al., 2025) provided the first comprehensive global synthesis of CoMF in coastal and estuarine regions, reviewing flood drivers, compound-event typologies, modelling approaches, climate-change influences, infrastructure implications, and future research needs. While this body of work has substantially advanced the scientific understanding of compound flooding, important gaps remain. In particular, relatively little attention has been devoted to integrating climatic drivers, modelling innovations, vulnerability assessment, flood-risk management, governance, forecasting systems, and climate adaptation within a single coastal-estuarine system. Consequently, there remains a need for place-based syntheses that demonstrate how advances in compound flood science can be translated into practical resilience and adaptation strategies. This review addresses that gap by positioning Cork Harbour as a coastal-estuarine living laboratory through which the evolution of compound flood science can be critically examined and translated into a transferable framework for modelling, risk management, governance, and climate adaptation in medium-sized estuaries worldwide. Unlike Green et al. (Green et al., 2025), which primarily focused on global patterns, processes, and methodological trends, the present review adopts an application-oriented perspective centred on the implementation of compound flood science in a real-world coastal-estuarine setting.

Across Europe, CoMF is a pressing natural hazard, particularly in low-lying coastal regions where the interaction of coastal and riverine processes is pronounced (Bevacqua et al., 2019; Philipp Heinrich et al., 2023a; P. Heinrich et al., 2023). Northern Europe faces persistent threats from coastal surges coinciding with high river flows, as illustrated by high-impact events in the Netherlands and Germany (Bevacqua et al., 2019; Philipp Heinrich et al., 2023a; P. Heinrich et al., 2023). Southern Europe, by contrast, often experiences compound rainfall–surge events in urbanised coastal catchments where rapid land-use change and insufficient drainage amplify flood hazard (Bevacqua et al., 2019; Philipp Heinrich et al., 2023a; P. Heinrich et al., 2023). Research across the United Kingdom, Ireland, the North Sea coast, and northwestern Europe has revealed increasing frequencies of compound riverine-coastal flood events, with climate change projected to further intensify the co-occurrence of meteorological and oceanographic extremes (Bevacqua et al., 2017; Bevacqua et al., 2019; Bevacqua et al., 2020; Ganguli et al., 2020; Philipp Heinrich et al., 2023a, 2023b; P. Heinrich et al., 2023). Consequently, other global recent reviews have also advanced understanding of compound flood mechanisms, assessment frameworks, uncertainty analysis, and modelling approaches, including hydrodynamic, statistical, and hybrid methodologies (Akter & Ataullah, 2025; Jahani et al., 2026; Ruan et al., 2024; Xu et al., 2023). While the comprehensive synthesis of Green et al. (Green et al., 2025) established the state of knowledge on CoMF globally, limited attention has been given to how advances in modelling can be translated into operational



flood-risk management, governance, climate adaptation, and resilience-building within coastal-estuarine systems. Addressing this gap is particularly important for representative Atlantic-facing estuaries such as Cork Harbour, where strong fluvial-coastal interactions, tidal amplification, urban exposure, and projected sea-level rise create conditions highly conducive to CoMF and provide a transferable testbed for developing adaptation-oriented flood-risk frameworks applicable to medium-sized estuaries across Europe and beyond.

In the Irish context, Urban centres such as Dublin, Cork, Galway, and Limerick face mounting risks as population growth and development intensify exposure in flood-prone areas (Jeffers, 2014; Paranunzio et al., 2022). The Cork Harbour and Catchment (CHC; Fig. 1) provides a particularly compelling setting for advancing compound flood science because it encompasses many of the characteristics that are increasingly defining flood risk in coastal-estuarine environments worldwide. Situated at the confluence of the River Lee catchment and the Atlantic Ocean, CHC is exposed to interacting fluvial, pluvial, coastal, tidal, and increasingly groundwater flood processes that operate across connected terrestrial, estuarine, and marine systems. Located in the south of Ireland and encompassing the country's second largest metropolitan area, CHC is of considerable national and regional strategic importance, functioning simultaneously as a major industrial port, socio-economic centre, tourism destination, recreational resource, and cultural heritage landscape (Brunt, 1980; COREPOINT, 2008; Cummins et al., 2008; Horgan, 1952). Historical evidence demonstrates the long-standing nature of flood risk within the region, with approximately 300 flood events recorded in Cork City between 1840 and 1988 (Tyrrell & Hickey, 1991). More recent events including the devastating November 2009 Cork City flooding (Jeffers, 2011; Nolan, 2019) and the widespread flooding experienced during the 2013–2014 and 2015–2016 winter storm seasons (Boudou et al., 2021; McCarthy et al., 2016; O'Brien et al., 2018), further reveal insights into the potential for compound flood events and highlighted the region's vulnerability to interacting hydrological and coastal processes. The 2009 flood event inundated large areas of the city centre, disrupted critical services and infrastructure, caused significant economic losses, and exposed deficiencies in forecasting, communication, and emergency preparedness systems (de Bruijn et al., 2016; Jeffers, 2011; Nolan, 2019). Likewise, County Cork was the worst affected region during the 2015-2016 winter floods, accounting for more than one-quarter of all recorded flood damage nationally (Irishexaminer, 2016). For example, during the 2015/2016 winter flooding event over 30 towns and villages, 540 homes and more than 600 businesses across Ireland experienced major flooding across Ireland, including Bandon, Co Cork; Athlone, Co Westmeath; and Castle Connell, Co Limerick (Irishexaminer, 2016). Similarly, in County Cork more than 155 homes and 135 business were affected (Irishexaminer, 2016).

Importantly, over the last decade, Cork Harbour has evolved into one of Europe's most intensively studied coastal-estuarine flood systems, providing a unique opportunity to examine how advances in compound flood science can be translated into practical adaptation and resilience outcomes. The harbour has served as a testbed for high-resolution hydrodynamic modelling (Comer et al., 2017; Nash et al., 2018; Olbert et al., 2017), coupled statistical-hydrodynamic approaches for compound flood assessment (Olbert et al., 2023), machine-learning and artificial-intelligence-based forecasting systems (Moradian et al., 2024;



Olbert & Moradian, 2024), groundwater flood assessment (Soboh et al., 2024, 2026), vulnerability of critical-infrastructure
160 (de Bruijn et al., 2016) and emerging climate-adaptation approaches including dynamic adaptive pathways planning
(Langendijk et al., 2025), social vulnerability (McCullagh et al., 2025), climate services (McCullagh et al., 2024), integrated
coastal zone management (O'Mahony et al., 2020), and participatory governance (Jeffers, 2020; Jeffers, 2022). Despite such
advances, there is a lack of systematic review that accounts for CoMF risk modelling, risk management, and climate adaptation
measures.

165 The scientific value of this review lies not in revisiting the global syntheses of CoMF literature already provided by several
studies (Akter & Atallah, 2025; Green et al., 2025; Jahani et al., 2026; Ruan et al., 2024; Xu et al., 2023), but in demonstrating
how advances in compound flood modelling, flood-risk management, governance, vulnerability assessment, and climate
adaptation can be integrated within a single coastal-estuarine system. By positioning Cork Harbour as a coastal-estuarine living
170 laboratory, this review develops a transferable framework for medium-sized estuaries worldwide and addresses a critical gap
in the contemporary literature: the translation of compound flood science into actionable, place-based resilience and climate-
adaptation pathways.

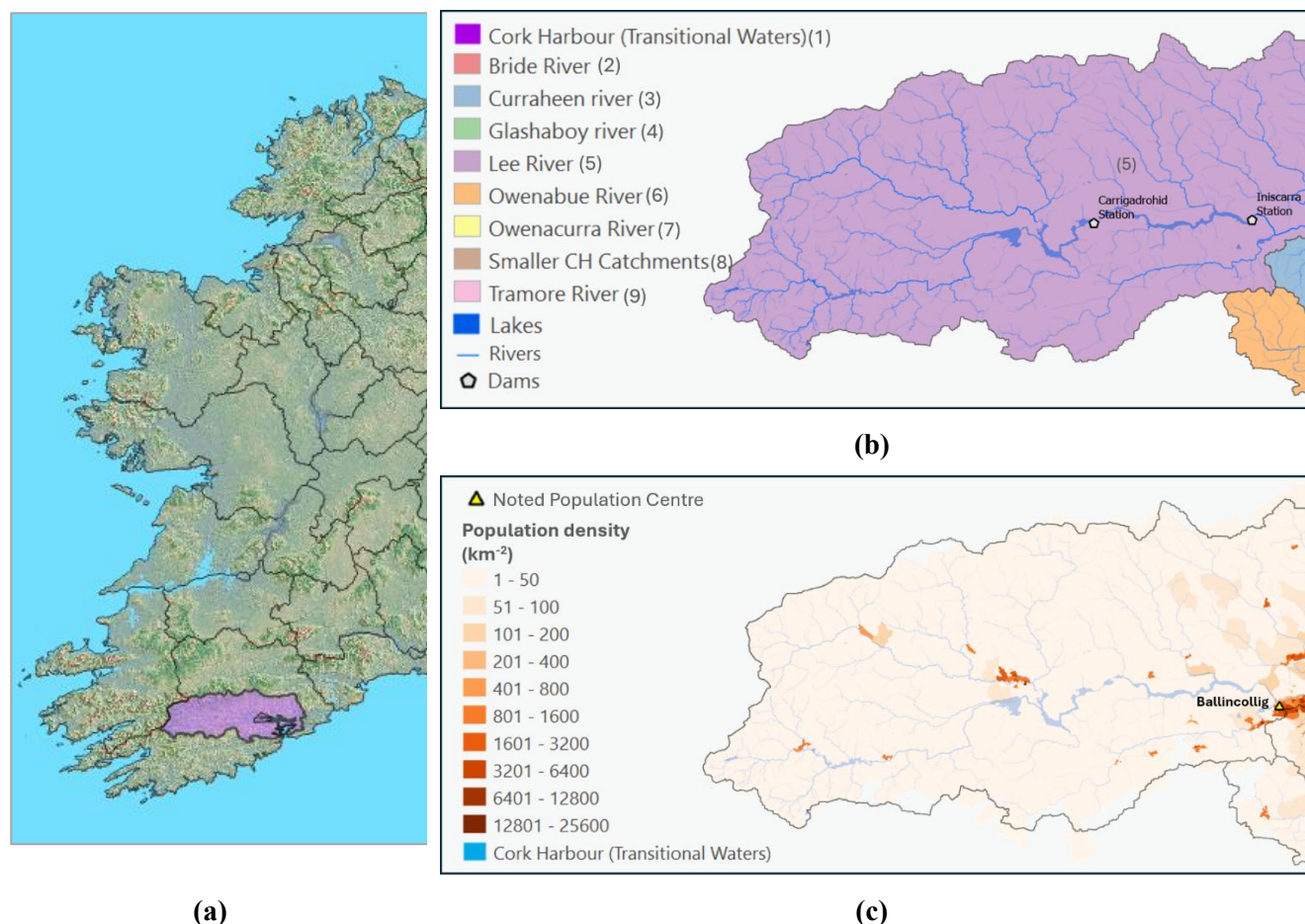


Figure 1: Cork Harbour (CH) and catchment, its population and catchment basin layout. Panel (a) shows the Island of Ireland, with the catchment location and extent highlighted in purple. Panel (b) shows the distribution of river catchments that are the source of waters flowing into the harbour, as well as large infrastructure features concerning river flow, and the general distribution of surface water features across the sub-basins. Catchments were generated using the Watershed tool in ArcGIS Pro and edited to align with local knowledge on river basins. Panel (c) shows the population characteristics of the catchment area and sub-basins, along with population centres noted in the text. Maps are displayed in UTM Zone 29N using the WGS1984 geoid. River and lake datasets are freely available from the Irish Environmental Protection Agency. Hillshades and watershed analysis used freely available SRTM elevation data.

Over the past two decades, Ireland has experienced growth in flood-related research (Adamson, 2018; Turner et al., 2010). These studies have examined diverse topics including flood hydrometeorology and gastroenteric infection (Boudou et al., 2021), coastal flood risk in Dublin (Paranunzio et al., 2022), integrated flood risk management (O'Neill, 2018), and extreme climate change impacts on coastal cities such as Sligo and Dublin (Laino & Iglesias, 2023, 2025). In the Irish context, a limited



number of reviews have addressed specific aspects of extreme climate change impacts on coastal cities (Laino & Iglesias, 2023), including impacts of extreme weather events and environmental contamination under climate change on coastal cities
190 (Laino & Iglesias, 2025), impacts of climate change and extreme weather events on ecosystems (Cheung et al., 2012; Eichelmann et al., 2025; Heath et al., 2012), and climate change indicators and adaptation strategies (De Bruin et al., 2024; Donnelly et al., 2004). However, these studies have typically focused on broader extreme climate change research involving a range of natural hazards, providing broad assessments that do not explicitly address CoMF.

195 In Ireland flooding research review has grown substantially, but integrated comprehensive, CoMF focused syntheses remain very limited. Notably, only two papers have reviewed and provided a critical literature analysis of flood research from an Irish perspective (Fenton et al., 2021; O'Neill, 2018). Fenton et al. (2021) reviewed on-farm roadway runoff characterisation and potential management options, while O'Neill (O'Neill, 2018) analysed integrated flood risk management, yet did not address multivariate coastal–fluvial hazards. These reviews did not integrate multi-driver flood dynamics, modelling approaches,
200 governance, and adaptation strategies into a unified compound-flood resilience framework. There are no other publications that have reviewed integrated compound flood risk modelling and management approaches in Ireland. The existing flood research knowledge base in Ireland remains fragmented across disciplines and application domains. At the regional level, this gap is also evident, with no published literature available to date that has synthesised the full body of compound flood research specifically related to Cork Harbour or Ireland more broadly. This is striking given Cork Harbour's repeated exposure to flood
205 events, and the drivers of CoMF, its hydrodynamic complexity, and the rapid expansion of CoMF literature globally (Akter & Ataulлах, 2025; Green et al., 2025). Additionally, the CHC represents a globally relevant case study for CoMF due to the coexistence of riverine, pluvial, coastal (tidal and storm surges), and groundwater flood drivers, yet there is a need for a comprehensive assessment of the research done to date.

210 This systematic review fills this critical gap by offering the first holistic, cross-disciplinary synthesis of CoMF in Cork Harbour across four dimensions: (i) climatic and hydrodynamic flood drivers, (ii) multi-scale and multivariate modelling, (iii) risk management and governance, and (iv) hybrid structural, non-structural, and Nature-based adaptation strategies. From an international perspective, this review serves as a testbed synthesis—demonstrating how compound flood science can be operationalised in real-world decision settings and how methodological advances can be translated into local governance and
215 adaptation outcomes. Because Cork's characteristics are widely shared across global estuaries, the insights derived here are transferable to coastal-urban regions worldwide.

Guided by PRISMA protocols (Moher et al., 2009; Page et al., 2021), this systematic review appraised three decades of compound-flood research relating to CHC. It synthesized current knowledge on compound flood research across climatic, modelling, risk management, and climate adaptation domains. This review was structured around five interrelated specific
220 objectives:



- i. Elucidate the climatic drivers shaping CoMF research in CHC;
- ii. Evaluate state-of-the-art compound flood modelling approaches that may be of relevance;
- iii. Appraise flood risk management and adaptation strategies with particular attention to structural, non-structural, and hybrid measures;
- 225 iv. Identify knowledge gaps and propose future research directions; and
- v. Outline globally relevant lessons and pathways toward climate-resilient management of compound floods.

By systematically organising disparate literature across the five specific objectives and identifying cross-cutting weaknesses and emerging opportunities, this review established a foundation for transformative compound-flood resilience in Ireland and offers a transferable framework for international climate-risk research. This review thereby positions Cork Harbour as a globally instructive case, offering a rich empirical foundation, methodological innovation, and governance insight to inform compound-flood adaptation across international coastal–urban contexts.

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2. Methodology

2.1 Review rationale and methodological positioning

This study adopts a systematic literature review (SR) approach to synthesise current knowledge on CoMF in coastal and estuarine catchments, using CHC as an internationally relevant exemplar through which to examine advances in modelling, flood-risk management, governance, and climate adaptation. It adopted a rigorous, multi-stage methodology integrating a SR with grey literature appraisal to synthesize current knowledge on CoMF in CHC (Fig. 2). The SR was guided by the Integrated Flood Risk Management (IFRM) framework conceptualization (Cumiskey et al., 2019; Klijn et al., 2015; Ran & Nedovic-Budic, 2016; van Herk et al., 2015), a conceptual model developed to synthesize and critically evaluate fragmented bodies of research on flood modelling, risk management, and climate change adaptation. Recently, Irish studies also advocated for an integrated flood risk management system in Ireland (O'Neill, 2018). Thus, this study moves beyond the description of compound-flood processes toward understanding how modelling, management, and adaptation strategies can be integrated within real-world socio-hydrological systems. Cork Harbour provides a suitable case study because of its well-documented flood history, extensive modelling efforts, growing adaptation initiatives, and strategic importance as a coastal-estuarine system experiencing increasing climate-related risks. Accordingly, the overall approach to this review is outlined in Figure 2. Firstly, a SR of peer-reviewed published materials was conducted, from which the current state of academic research was extrapolated, along with research gaps identified to guide future inquiry and advance knowledge. Secondly, a search of grey literature was used to obtain additional information which served to contextualise the more academic findings and ground them in the reality of management, policy and societal action in response to flooding challenges.

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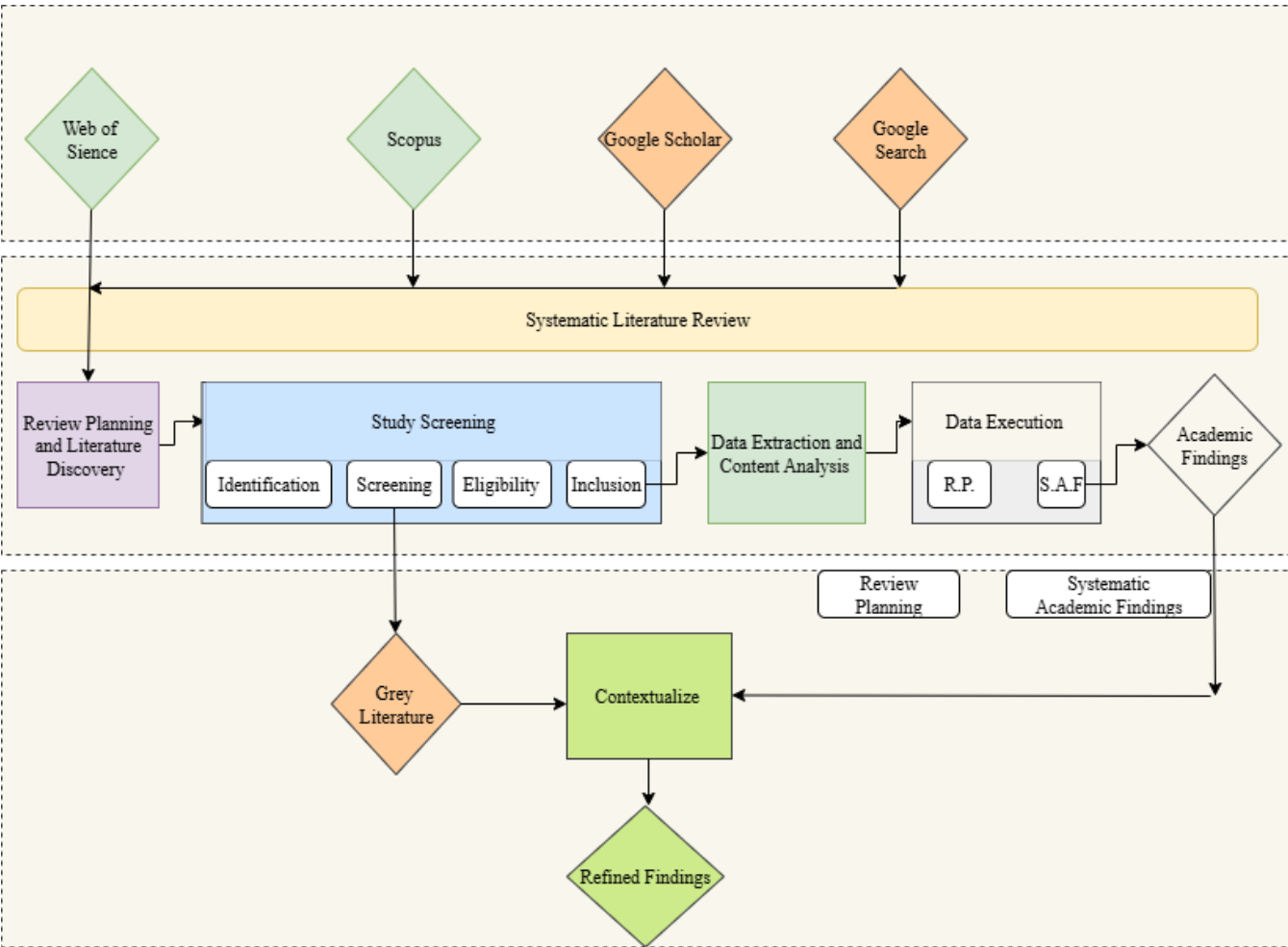


Figure 2. The research approach showing the two research phases. Input literature sources and findings are shown using diamonds, while review activities and processes are shown as rectangles.

2.2 Review framework and analytical approach

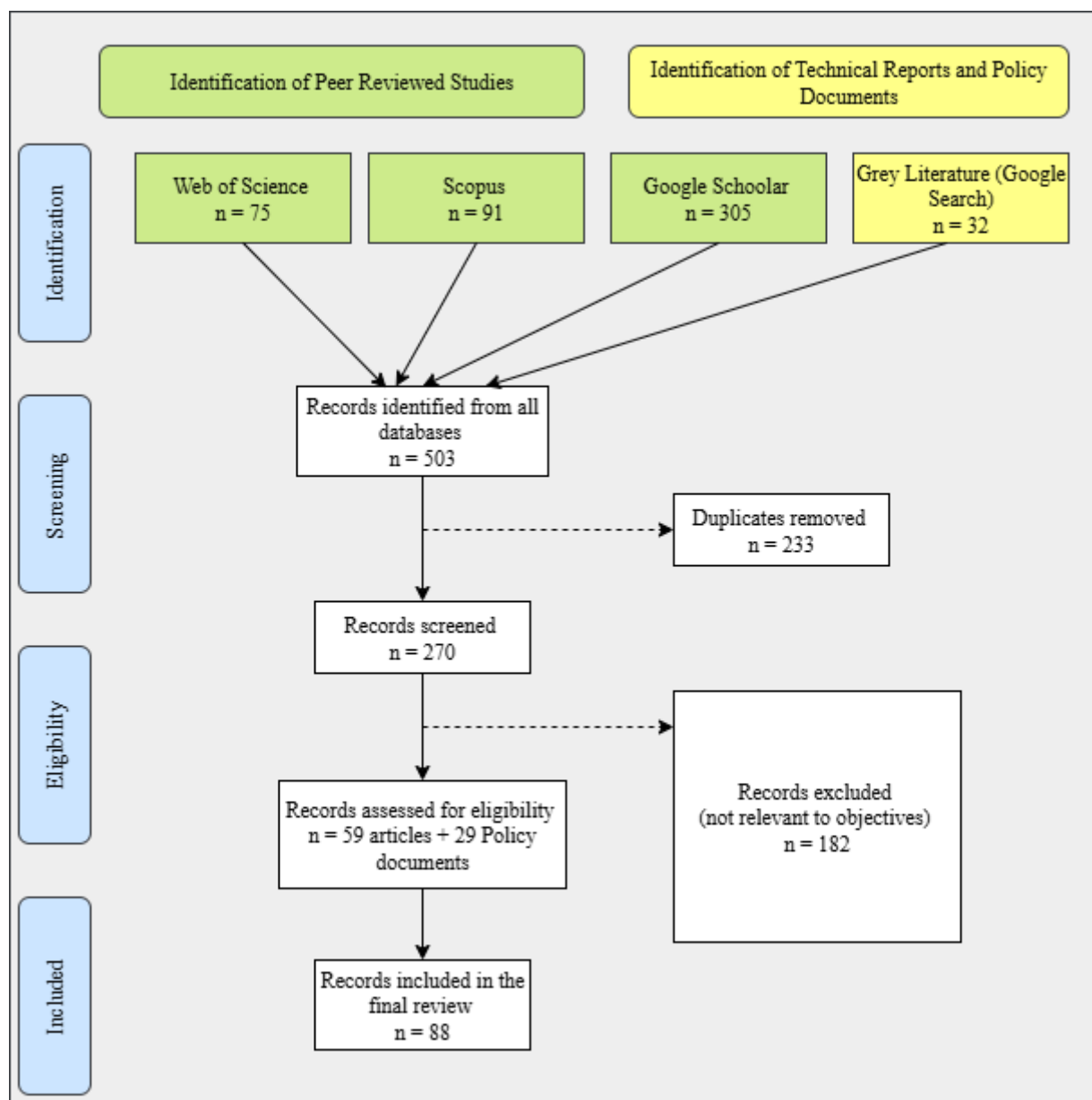
255 The review follows internationally recognised principles for systematic evidence synthesis and was informed by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Moher et al., 2009; Page et al., 2021). The SR adhered to PRISMA guidelines to ensure transparency, reproducibility, methodological robustness and it was conducted using a four-step process (Figure 2):

- i. Review planning by establishing the research criteria to identify relevant studies, and literature discovery to gather all potential articles and bodies of work;



- ii. Screening studies to assess eligibility by delineating the inclusion and exclusion criteria. The article selection process is applied at this step and is comprised of four key phases: Identification, Screening, Eligibility, and Inclusion (Moher et al., 2009; Page et al., 2021)
- iii. Data extraction and content analysis by performing a detailed reading and evaluation of the full texts; and
- 265 iv. Data execution, through research profiling before synthesis of the academic research findings (Fig. 3).

Given the interdisciplinary nature of compound flooding, the review combines systematic peer reviewed and grey literature searching with qualitative thematic synthesis and conceptual integration. Following PRISMA 2020, 503 records were identified and screened, with 87 items meeting the inclusion criteria—59 peer-reviewed articles and 28 technical/policy reports published between 1991 and 2025 (Fig. 3). The analytical framework comprised four interconnected domains including
270 climatic and hydrodynamic drivers, compound flood modelling and forecasting, flood risk management, and climate adaptation. This structure reflects the central objective of the paper: understanding not only compound-flood processes but also their implications for risk management and climate change adaptation.



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Figure 3. PRISMA flow diagram for the SR process and protocols for quality assessment process.



2.3 Literature search strategy

2.3.1. Review planning and literature discovery search strategy

280 A comprehensive literature search was conducted across major scientific and policy databases to identify relevant publications
on compound flood climatic drivers, flood modelling, risk management, and climate adaptation. Initially, the literature research
was conducted to capture the multi-dimensional aspects of CoMF in Cork Harbour. The primary databases included: Web of
Science Core Collection, Scopus, and Google Scholar. Targeted Google searches were also undertaken to ensure coverage of
policy and practice-oriented grey literature from Office of Public Works (OPW), Environmental Protection Agency (EPA
285 Ireland), Marine Institute Ireland, Government of Ireland publications, Cork City Council, Catchment Flood Risk Assessment
and Management (CFRAM) studies, and European Commission reports. The preliminary search string was developed using
“compound flood*” as the primary keyword, which was then refined and expanded to include related terms such as “flood
modelling”, “flood management”, “adaptation strategies”, “Cork Harbour”, “Cork City”, and “Climate change”. The search
strategy employed a combination of controlled vocabulary and free-text search terms using Boolean operators (AND, OR).

290 2.3.2. Study screening

Academic studies or policy and practice-oriented literatures were included when they met one or more of the inclusion criteria
mentioned in Table 1. Academic research articles were defined as the primary unit of analysis for the SR. Inclusion and
exclusion criteria (Table 1) were established to identify relevant studies that were most pertinent to the CoMF risk analysis in
CHC. In the screening processes the titles and abstracts of the selected papers were independently reviewed by two researchers
295 using Rayyan software, a web and mobile tool for collaborative systematic review (Ouzzani et al., 2016).



Table 1. Inclusion and exclusion criteria.

Inclusion Criteria (IC)	Exclusion Criteria (EC)
IC1. Published peer-reviewed journals, conference proceedings, government reports, or authoritative technical reports written in English	EC1. Studies not addressing impacts of climate change on flooding, flood modelling, flood risk management or flood risk adaptation
IC2. Studies focusing on CoMF or interacting flood drivers, modelling, forecasting, management, or adaptation strategies in CHC	EC2. Articles not written in English
IC3. Studies focusing on CoMF dynamics, including interactions between fluvial, pluvial, and coastal flooding	EC3. Articles not focusing on flood risk in CHC
IC4. Studies discussing the impacts of climate change on flooding in the region	EC4. Articles that do not discuss flood modelling, management, or adaptation strategies in CHC
IC5. Peer-reviewed journal articles, conference papers, technical reports, and high-quality reports from governmental or research institutions	EC5. Studies with insufficient methodological transparency (e.g., lacking details on flood modelling approaches, climate impact analysis, or flood risk management and adaptation)
IC6. Articles that characterise landcovers and land uses that shape flooding dynamics of the catchment	EC6. Duplicate publications
IC7. Articles available in full text	EC7. Full text article was not available / accessible

2.3.3. Data extraction

305 Data extraction was initiated by full text content reading and evaluation using a standardised data extraction sheet. Evaluation
 focused on extracting detailed information on compound flood drivers (e.g., fluvial–coastal, pluvial–tidal), modelling
 approaches (e.g., hydrodynamic, statistical, data-driven, coupled), management strategies (e.g., structural defences, early
 warning systems, governance models), and adaptation strategies (e.g., nature-based solutions, policy reforms, infrastructure
 design). Studies were then classified into three thematic domains: (i) Modelling and simulation, (ii) Risk management and
 governance, and (iii) Climate adaptation strategies. This taxonomy enabled cross-comparison and findings synthesis across
 310 disciplinary boundaries.

2.4. Data execution and thematic synthesis

Data were systematically extracted into a structured review matrix. The synthesis generated the following principal thematic
 categories: climatic drivers of flooding in Cork Harbour; advances in hydrodynamic modelling; coupled statistical–



hydrodynamic modelling; machine learning and AI-enhanced forecasting; flood-risk vulnerability assessment; structural
315 adaptation measures; non-structural adaptation measures; integrated coastal and catchment management; governance and
stakeholder participation; nature-based solutions, and hybrid adaptation solutions.

2.4.1. Synthesis of academic findings

A narrative synthesis approach was employed to integrate findings across the three thematic classifications (Modelling and
simulation, risk management and governance, climate adaptation strategies). Inter-relationships among the themes were then
320 identified. This systematic approach facilitated a nuanced understanding of the state-of-the-art in compound flood risk analysis,
including its modelling techniques, management practices, and adaptation strategies. The literature synthesis provided the
foundation for the subsequent discussions on research gaps, future research avenues, and practical and theoretical implications.

2.4.2. Contextualisation using grey literature

Recognising that peer-review publications primarily target more academic audiences, while actionable information is more
325 often found in reports, the segregated grey literature was used to provide policy, management and perspective during the
contextualisation phase of the work. Consideration of this information is presented here in the discussion section, while the
results focus on the core outputs of the SR.

3. Results

330 The systematic review identified a rapidly growing body of literature on CoMF in coastal and estuarine systems, with CHC
emerging as a particularly informative and internationally relevant case study. Following the PRISMA framework, peer-
reviewed publications, technical reports, and policy documents relating to CoMF in Cork Harbour and its catchment were
systematically screened, evaluated, and synthesised. The resulting evidence base spans four interconnected domains: (i)
climatic flood drivers, including fluvial, pluvial, tidal, and storm-surge influences; (ii) flood predictive intelligence,
335 encompassing hydrologic and hydrodynamic modelling, multivariate statistics, and machine learning; (iii) operational flood
risk management intelligence, including forecasting, early-warning systems, and risk governance; and iv) long term adaptative
intelligence for changing climate, covering adaptation pathways, resilience-building strategies, and transformative flood-risk
management approaches. Together, these domains reveal a multi-layered source-to-sea understanding of compound flood risk
within CHC. The climatic drivers, the three intelligence layers, and their interactions, together with the cross-cutting themes
340 that emerged from the synthesis, are presented in the following sections.

3.1 Climatic drivers of compound flooding in CHC

Flooding in Cork Harbour arises from the interaction of four principal climatic and hydrological drivers: (i) fluvial flooding
from the River Lee and its tributaries; (ii) pluvial flooding driven by intense rainfall and runoff; (iii) coastal flooding associated



345 with sea-level rise, storm surges, and tidal dynamics; and (iv) groundwater flooding linked to prolonged wet conditions and elevated water tables. While each mechanism can independently trigger damaging events, evidence increasingly shows that Cork Harbour's most severe flood events stem from compound interactions (Kirkpatrick et al., 2020; Kirkpatrick & Olbert, 2020).

350 **3.1.1 Inland flooding drivers**

Heavy precipitation

Extreme precipitation is the most frequent and economically disruptive natural hazard in Ireland (Nolan, 2025), and is the principal trigger of both fluvial and pluvial flooding in the River Lee catchment (part of the CHC) (Kirkpatrick & Olbert, 2020). Flood generation is strongly influenced by the River Lee system and its tributaries, where sustained rainfall, antecedent
355 soil moisture conditions, and reservoir operations interact to determine downstream discharge patterns (Comer et al., 2017; de Bruijn et al., 2016; Kirkpatrick & Olbert, 2020; Olbert et al., 2017). High antecedent soil moisture conditions constrained catchment storage, thereby amplifying runoff generation and promoting rapid hydrological responses within the River Lee and its tributaries immediately upstream of Cork City (Olbert et al., 2017). Multiple national climate model ensembles consistently indicate that Ireland's precipitation regime is shifting toward higher seasonality and greater volatility, with wetter autumns and
360 winters and more intense rainfall extremes (Nolan, 2015; Nolan & Flanagan, 2020; Nolan et al., 2017). By mid-century, ensemble projections estimate increases of approximately 20% in heavy precipitation, accompanied by a 24% rise in "wet days" (>20 mm) and a 30% rise in "very wet days" (>30 mm) during winter (Nolan et al., 2017). Under high-emissions scenarios (SSP5–8.5), very wet days are projected to increase annually by ~31%, and by up to 61% in winter and 71% in autumn (Nolan & Flanagan, 2020). This upward trend is robust across modelling frameworks, despite uncertainties in
365 convective rainfall processes, translating directly into heightened flood risk in Cork. Documented heavy rainfall events have contributed to flooding in parts of the south-eastern counties of Ireland (Bergin et al., 2025) particularly those associated with rapidly increased runoff, saturated soils, and elevated river discharges, intensifying fluvial flooding and overwhelming urban drainage systems. Modelling studies indicate that heavy rain is expected to notably strain Cork's urban drainage, increasing the occurrence of pluvial flooding, especially on the low-lying central island where impermeable surfaces dominate
370 (Kirkpatrick & Olbert, 2020). The implications for CHCs are profound, where increased precipitation can contribute to more frequent and severe fluvial and pluvial flooding (Kirkpatrick & Olbert, 2020). Heavy precipitation is anticipated to intensify fluvial flooding by increasing peak river discharges, thereby introducing additional strain on drainage systems and increasing the likelihood of CoMF (Kirkpatrick et al., 2020; Kirkpatrick & Olbert, 2020; Moradian et al., 2023).

375 ***River flows, groundwater dynamics, and hydrological amplification***

The hydrological response of the Lee catchment to changing climate conditions reflects not only enhanced precipitation but also shifts in evaporation and soil moisture regimes that are likely to be reflective of the wider CHC. Long-term river flow records show increasing trends in annual and winter high flows, a pattern projected to intensify under future climate scenarios.



Hydrological modelling across Irish catchments demonstrates that winter (months of October to April) stream flows could rise by up to 20% by mid-century, with January and February showing the largest increases (Charlton et al., 2006; Steele-Dunne et al., 2008). Larger catchments such as the Lee generally exhibit moderate but persistent increases, while smaller neighbouring catchments such as the Bandon and Blackwater show more extreme variability and higher sensitivity to heavy rainfall events (Bastola et al., 2011a, 2011b; Murphy et al., 2023; Steele-Dunne et al., 2008). Under the Representative Concentration Pathway (RCP) 8.5, high flows may increase by up to 59.6%, and flood flows by up to 116% by the 2080s (Murphy et al., 2023).

In Cork, these hydrological changes translate into substantially elevated fluvial flood hazards. For example, Halcrow (Halcrow, 2009) projected up to 20% increases in peak flow in the Lee by 2100, while OPW ensemble modelling suggests increases of c.30% (OPW, 2015, 2019). Modelling by Kirkpatrick et al. (2020) and Kirkpatrick and Olbert (2020) confirms that fluvial processes remain the dominant component under present climate conditions, with a 100-year return period flow (c.512 m³/s) inundating c.187 ha (Kirkpatrick et al., 2020; Kirkpatrick & Olbert, 2020). Under enhanced flow scenarios such as Hydrologic Ensemble Forecast Service (HEFS) (728 m³/s), the flooded area expands to 242 ha, a 30% increase, with large sections of Cork's central island submerged (Kirkpatrick et al., 2020; Kirkpatrick & Olbert, 2020). Cork Harbour is vulnerable to groundwater flood and the groundwater dynamics further modulate inland flood risk (Allen & Milenic, 2007). Although more pronounced in western karstic regions, groundwater flooding can occur in Cork City (Allen & Milenic, 2007; Soboh et al., 2026) following prolonged saturation, raising baseflows and compounding surface flood hazards. Soboh et al. (Soboh et al., 2026) investigated coastal groundwater flooding in Cork City and found that groundwater levels, influenced by sea-level-rise-induced emergence, retained approximately 70–100% of the adjacent river's tidal fluctuations.

3.1.2 Coastal flooding drivers

The review identifies storm surge, astronomical tides, sea-level rise, and wave processes as the dominant coastal flood drivers affecting Cork Harbour. Cork Harbour's coastal flood vulnerability is strongly conditioned by its low-lying estuarine topography. As with other Irish coastal cities (Dublin, Galway, Limerick), Cork's waterfront infrastructure, reclaimed lands, and central island are particularly susceptible to even minor increases in sea level or surge levels.

Sea-level rise (SLR)

SLR is one of the most consequential climatic drivers affecting Cork Harbour. Tide-gauge data indicate that mean sea level in Cork has risen ~40 cm from 1842–2019, consistent across three stations—Currach Club, Ringaskiddy, Ballycotton—which differ by ≤1 cm in modern records (Pugh et al., 2021). Projections suggest further SLR of 0.5 m (MRFS) to 1.0 m (HEFS) by 2100 for the region (Halcrow, 2009; OPW, 2015, 2019). SLR not only raises baseline water levels but reduces the return period of present-day extreme events. Under 0.5 m SLR, c.200 km² of coastal land nationally faces inundation, with Cork among the highest-risk counties. A 1 m SLR scenario would expose ~30% of Ireland's coastal area, with catastrophic implications for Cork's harbour-front districts (Devoy, 2008).



Storm surges and tide–surge interactions

415 Beyond SLR, storm surges and their interactions with astronomical tides play a pivotal role in Cork’s coastal flood hazards. Numerical modelling shows that extreme surge heights (50–100 cm) around Irish coasts may increase by up to 20% under future climate scenarios (Wang et al., 2008). Olbert and Hartnett (2010) demonstrated that a 1 mbar drop in atmospheric pressure produces ~1.2 cm sea-level rise, with inverted barometer effects contributing >80% of surge residuals in the Celtic Sea. Tide–surge interactions modulate both the phase and amplitude of extremes, yielding highly site-specific water level
420 responses. For Cork, observed maxima for tides, surges, and total water levels are 0.81 m, 4.50 m, and 4.96 m, respectively (Olbert et al., 2013). Extreme water-level modelling shows that 200-year return period events may reach 5.14 m (Olbert et al., 2013), exceeding thresholds of some existing defences. Meanwhile, long-term tidal analyses confirm subtle but climatically relevant shifts. Over the 177 years (1842–2019) period, the amplitude of the M2 tidal constituent, the principal lunar semidiurnal tide, increased by 3.0 ± 0.5 cm in Cork Harbour, while its phase advanced by approximately four minutes (Pugh
425 et al., 2021). Although modest, these changes can influence the timing and magnitude of water-level exceedances and may therefore affect the severity of compound flood events.

3.1.3 Climate change and compound flood risk

Recent studies have increasingly focused on the implications of climate change for CoMF focusing on urban coastal-fluvial
430 flooding in coastal city of Cork, Ireland (Kirkpatrick et al., 2020; Kirkpatrick & Olbert, 2020). Kirkpatrick and Olbert (2020) examined the impacts of sea-level rise and changing hydrological conditions on urban coastal-fluvial flooding and demonstrated that future flood hazards are likely to increase substantially under projected climate scenarios. Their analyses highlighted that sea-level rise acts as a persistent hazard amplifier, increasing baseline estuarine water levels and reducing hydraulic drainage capacity during high-flow events. Consequently, moderate storm or riverine events may produce impacts
435 comparable to those currently associated with extreme floods. Under worst-case future projections, coastal inundation may increase by ~400%, shifting dominance from fluvial to coastal mechanisms (Kirkpatrick & Olbert, 2020). Climate-driven increases in sea level and storm-surge intensity could increase coastal inundation from 38 ha to 191 ha, representing a fourfold expansion and surpassing the extent of current extreme fluvial flooding (187 ha) (Kirkpatrick & Olbert, 2020). Nevertheless, future extreme fluvial events are still projected to produce the largest inundation extent, reaching up to 242 ha. Nevertheless,
440 future extreme fluvial events are still projected to produce the largest inundation extent, reaching up to 242 ha. Combined effects of increased fluvial flows and amplified coastal levels could inundate ~387 hectares —a 76% increase relative to the 100-year flood event of November 2009 (Kirkpatrick & Olbert, 2020).

Similarly, Kirkpatrick et al. (2020) demonstrated that future flood behaviour in Cork City is likely to be characterised by
445 increasingly complex interactions among urban development, sea-level rise, precipitation extremes, and coastal dynamics. Under high-end coastal forcing scenarios, flooding becomes widespread across Cork City, including large sections of the



central including large sections of the central street network and the Marina industrial area south of the River Lee (Kirkpatrick et al., 2020). Overtopping along Albert Quay and Kennedy Quay facilitates the eastward spread of floodwaters towards Victoria Road and Centre Park Road (Kirkpatrick et al., 2020). The greatest simulated coastal inundation covers approximately 191 ha and occurs when an extreme storm-surge event coincides with a high-end mean sea-level rise (MSLR) scenario (Kirkpatrick et al., 2020). These findings reinforce the need for climate-informed modelling frameworks capable of evaluating adaptation options under multiple future scenarios.

From a climate change perspective, CHC represents an ideal natural laboratory for assessing climate-related compound flood risk, owing to its strong coupling of riverine and coastal processes, high concentrations of exposed assets, and extensive history of flood modelling and risk assessment. The reviewed literature consistently demonstrates that climate change is fundamentally altering the flood hazard dynamics through concurrent changes in both inland and coastal drivers. On the terrestrial side, increases in extreme precipitation, increased river discharges, and growing hydrological non-stationarity are expected to intensify both fluvial and pluvial flooding. Simultaneously, rising mean sea levels, more impactful storm surges, and evolving tidal conditions are projected to increase coastal flood exposure. The simultaneous intensification of these drivers is likely to increase the frequency and severity of compound flood events, underscoring the importance of integrated compound flood modelling, risk management, and adaptation strategies across the entire catchment–estuary–coast system.

3.2 Modelling of compound flood risk in CHC

3.2.1 Advances in hydrodynamic modelling

Hydrodynamic modelling has been the primary driver of methodological advances in compound flood research within CHC. In particular, the development of the high resolution, Multi-Scale Nested Flood Model (MSN_Flood) framework represents a major step forward, providing an integrated platform for simulating the multi-scale interactions between riverine flows, estuarine dynamics, and coastal water levels that underpin compound flood risk (Comer et al., 2017; Hartnett & Nash, 2017; Nash et al., 2018; Olbert et al., 2017). Olbert et al. (2017) pioneered urban-scale compound flood modelling in the Cork City. They developed a high-resolution modelling system capable of dynamically simulating interactions among tides, storm surges, river inflows, and urban floodplain processes within Cork Harbour and Cork City. The modelling framework linked a large-scale ocean model of the northeast Atlantic with successively nested hydrodynamic domains, ranging from harbour-scale simulations to two-metre-resolution urban floodplain modelling, enabling accurate representation of flood propagation pathways from the coastal ocean to individual city streets (Olbert et al., 2017). In this high-resolution urban flood modelling the four nested grids extend from 90 m in outer Cork Harbour through to 30m in the inner waters of the harbour, 6m in the River Lee estuary and 2 m in the inner streets of Cork city (Nash et al., 2018; Olbert et al., 2017). Validation against the



November 2009 flood demonstrated the model's capacity to reproduce observed inundation extents and flow patterns, confirming the model's adequacy for both hindcasting and scenario analysis (Olbert et al., 2017).

480 Building upon this work, Comer et al. (2017) further advanced the MSN_Flood framework through the implementation of dynamically linked nested grids that improved simulation efficiency while maintaining high spatial accuracy. Comer et al. (2017) They expanded on these foundations by describing the model's technical innovations, particularly its "ghost-cell" nesting scheme and adaptive interpolation algorithms, which allow seamless transition between nested domains and maintain numerical stability across wet-dry interfaces. These features enable the model to simulate complex estuarine dynamics, including the modulating influence of tidal stage on river flood wave propagation. Their results demonstrated that flood behaviour within Cork City is strongly governed by interactions among river discharge, tidal conditions, and storm-surge forcing, underscoring the importance of integrated modelling approaches in estuarine environments. Similarly, Hartnett and Nash (2017) demonstrated the capability of high-resolution urban flood models to reproduce detailed flood hydraulics and inundation patterns within densely developed urban areas.

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Subsequent work by Nash et al. (2018) highlighted the value of ultra-high-resolution urban flood simulations for investigating compound coastal-fluvial flooding under a range of hydrological and tidal scenarios. They further advanced the MSN_Flood approach by embedding it within a cascade of four nested grids and coupling it dynamically to a three-dimensional Princeton Ocean Model (POM) for the North-East Atlantic. This integration ensured physically consistent surge boundary conditions, an essential component in Cork Harbour where remote storm systems influence surge propagation. Using LiDAR-derived topographic data and high-resolution bathymetry, the model successfully reproduced key characteristics of the 2009 event. Their analysis revealed a non-linear relationship between river discharge and inundation, where flows $>500 \text{ m}^3 \text{ s}^{-1}$ triggered extensive flooding irrespective of tidal phase (Nash et al., 2018). Their findings showed that flood severity within Cork City increases nonlinearly as river discharges interact with elevated tidal levels, further emphasizing that flood hazards cannot be adequately represented through single-driver analyses. These findings demonstrate that physically based hydrodynamic models are indispensable for capturing the multi-scale interactions characteristic of Cork Harbour's compound flood regime. The capacity to resolve both broad-scale coastal circulation and fine-scale street inundation within a single modelling framework is a defining strength of the MSN_Flood system and underpins its continued use in regional risk assessments (Comer et al., 2017; Hartnett & Nash, 2017). Collectively, these studies represent a progression from conventional flood modelling towards physically based representations of compound flood dynamics that explicitly account for estuarine interactions, tidal amplification, and urban inundation processes. The resulting modelling frameworks have become foundational tools for understanding flood risk within CHC and provide a template for similar applications in other coastal-estuarine systems.

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3.2.2 Coupled statistical-hydrodynamic modelling approaches

While hydrodynamic models remain the cornerstone of compound flood analysis due to their ability to simulate complex flood dynamics with high physical realism, they offer limited insight into the likelihood of infrequent but high-impact compound events. Consequently, recent studies have increasingly integrated statistical and hydrodynamic methods, particularly through the coupling of multivariate extreme-value analysis with process-based simulations (Olbert et al., 2015; Olbert et al., 2023). Recognising that compound flood events are inherently probabilistic and multivariate, recent studies have coupled hydrodynamic models with extreme value statistics to more robustly quantify risk under both present and future climate conditions (Olbert et al., 2015; Olbert et al., 2023). Olbert et al. (2015) assessed mechanisms of flooding in Cork City by involving both probabilistic and deterministic modelling approaches.

A major advancement in this area was provided by Olbert et al. (2023), who developed a combined statistical-hydrodynamic framework for assessing CoMF in coastal environments. Olbert et al. (2023) developed an eight-step multivariate dependency–inundation framework that links statistical extreme-value analysis with high-resolution hydrodynamic modelling to assess coastal–fluvial compound floods in Cork. Their methodology integrates multivariate statistical analyses with physically based hydrodynamic simulations, enabling the estimation of flood hazards associated with low-frequency, high-consequence events that may not be represented within historical records. The method explicitly captures dependencies between surge residuals, tides, and river flows, generates joint-probability flood scenarios, and propagates them through nested models to map inundation depth, extent, and hazard (Olbert et al., 2023). Their simulations revealed that Cork City is particularly sensitive to high fluvial inflows, which propagate through the west–east corridor of recreational fields and arterial streets before ponding in the low-lying central island. Figure 4 shows maximum water depths due to the river flood wave propagating through the city floodplains for 50 and 200-year return period (RP) river flows. For 50 (Fig. 4a) and 200-year (Fig. 4b) RP discharges, inundation expands rapidly over ~10 hours, and in the worst-case 200-year scenario (Fig. 4c), total inundation reaches ~75.9 ha (Olbert et al., 2023). While moderate tidal levels slightly amplify flooding, extreme scenarios demonstrate the decisive role of river discharge in controlling the onset and extent of urban inundation.

The integration of statistical and hydrodynamic methods therefore represents one of the most major developments within compound flood modelling over the past decade. The information derived from the coupled modelling methodology can provide important information for long term planning, investment decisions concerning flood defence infrastructure, and quantification of probable flood damage of economic, social and environmental natures (Kirkpatrick et al., 2020; Kirkpatrick & Olbert, 2020; Olbert et al., 2023). Outside of Cork City, in the Cork Harbour region, applications of the approach are still needed for neighbouring harbour catchments, and their downstream populated areas (e.g. Carrigaline and the River Owenabue, Glanmire and Glashaboy River, Middleton and the Owenacurra River, which collectively are home to a considerable



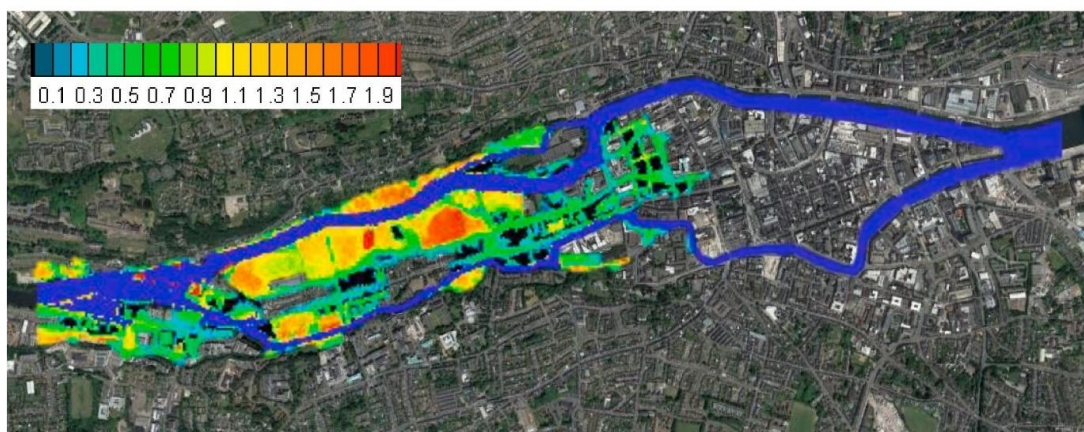
540 population). At these locations, there is the potential for a greater variability in the balance of flood drivers to appear, which would need to be considered in any flood mitigation or adaptation strategy.



(a)



(b)



(c)

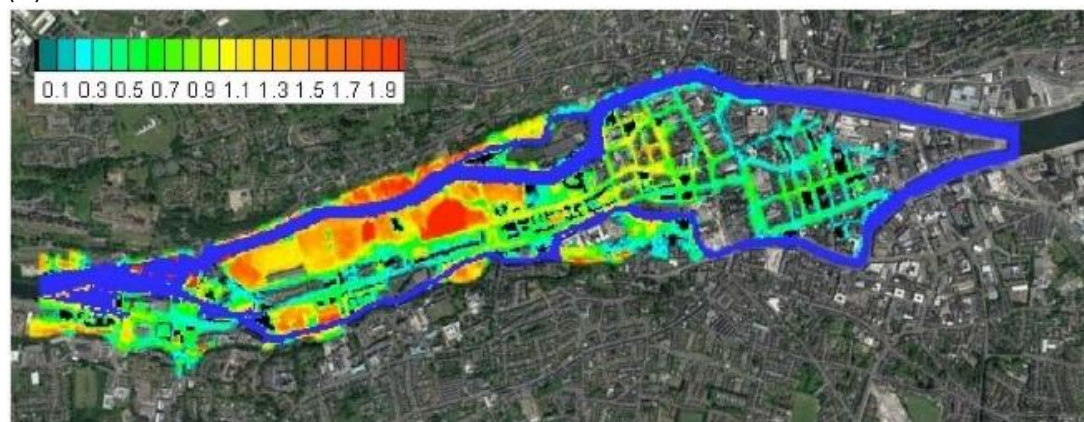




Figure 4. Maps of maximum water depths (m) due to fluvial flood wave moving through Cork City. River discharge of (a) 50-year RP, (b) 200-year RP and (c) coastal-fluvial flood for a 200-year joint exceedance RP (Olbert et al., 2023).

3.2.4 Integrating machine learning with hydrodynamic simulations

One of the most rapidly developing areas of compound flood modelling involves the integration of artificial intelligence (AI) and machine-learning (ML) techniques with hydrodynamic frameworks (Moradian et al., 2024; Olbert & Moradian, 2024). Moradian et al. (2024) demonstrated the potential of machine-learning algorithms for forecasting compound ocean-fluvial floods, showing that data-driven approaches can significantly improve forecasting speed while maintaining high predictive skill. They introduced a two-step hybrid framework for forecasting compound ocean-fluvial floods by integrating hydrodynamic simulations with ML algorithms such as Support Vector Regression (SVR), Radial Basis Functions (RBF), Gaussian Process Regression (GPR), Decision Trees, and Artificial Neural Networks (ANN). By training ML models on hydrodynamic outputs, they achieved improved forecasting of coastal-fluvial flooding with limited hydraulic and hydrological input data (Moradian et al., 2024). The RBF model produced the highest predictive performance, offering substantial improvement in early warning capability and operational readiness (Moradian et al., 2024).

Expanding on this work, Olbert and Moradian (2024) proposed a novel approach to flood forecasting by combining statistical, hydrodynamic, and ML models. The coupled statistical-hydrodynamic-ML system exploits the strengths of each modelling paradigm: statistical models capture joint likelihoods, hydrodynamic models offer physical realism, and ML models deliver computational efficiency (Moradian et al., 2024; Olbert & Moradian, 2024). Such hybrids are particularly well suited to operational flood forecasting, where timeliness and predictive skill are equally important. For CHC, these developments have particular significance because they provide a pathway toward digital-twin-based flood management systems capable of integrating observations, forecasts, hydrodynamic simulations, and management interventions within a single adaptive framework.

3.2.5 Estimating flood exposure, vulnerability, and risk

The literature also reveals a growing recognition that flood hazard modelling alone is insufficient for evaluating compound flood risk. While substantial progress has been made in simulating physical flood hazard dynamics, flood consequences ultimately depend upon interactions among hazard, exposure, vulnerability, and adaptive capacity. Studies following the 2009 Cork flood highlighted the importance of considering social and institutional dimensions of flood risk (Jeffers, 2011, 2013, 2014). Jeffers (Jeffers, 2011, 2013, 2014) argued that flood impacts are shaped not only by physical hazards but also by historical development patterns, governance structures, exposure, vulnerability, and risk perception. Jeffers highlighted that while physical hazard modelling has advanced substantially, the socio-ecological vulnerability dimensions (exposure, sensitivity, adaptive capacity or resilience) of flood risk remain understudied in the CHC region (Jeffers, 2011, 2013, 2014).



Recent advances have further expanded vulnerability assessments through the incorporation of socio-environmental indicators (McCullagh et al., 2025), climate services (McCullagh et al., 2024), and vulnerability of critical infrastructure (de Bruijn et al., 2016). McCullagh et al. (2025) developed a social vulnerability index specifically designed to support climate justice and adaptation planning in Ireland. These developments represent an important shift toward people-centred risk assessment and provide mechanisms for integrating equity and resilience considerations into compound flood management. Promising approaches have emerged to develop social vulnerability indices across climate services using multi-indicator indices combining socio-demographic, infrastructural, and environmental variables (McCullagh et al., 2025; McCullagh et al., 2024). These frameworks incorporate exposure (e.g., older housing stock, impervious surface cover), sensitivity (e.g., age, disability, health), and adaptive capacity (e.g., income, education, mobility, tenure) (McCullagh et al., 2025). The current flood risk management approach emphasises physical exposure and largely ignores socio-economic vulnerability (Jeffers, 2011). Thus, incorporating a broader range of information sources and data types into risk and vulnerability assessments may illuminate more creative strategies for reducing both contemporary and future flood losses (Jeffers, 2014). These lines of research could be strengthened, with future studies focusing on how inequities to flood exposure and damage can be managed. However, this would require deliberate indicator selection and careful statistical treatment to avoid over-representation of correlated indicators.

In parallel, climate-service initiatives in Cork City have begun linking scientific information with adaptation decision-making processes (McCullagh et al., 2024). McCullagh et al. (2024) demonstrated how the co-development of climate services can improve communication among scientists, policymakers, and stakeholders, thereby facilitating more effective implementation of adaptation measures.

At the infrastructure level, de Bruijn et al. (2016) demonstrated vulnerabilities within critical infrastructure systems in Cork City, highlighting the cascading consequences that flooding can generate across transport, utility, and service networks. These findings reinforced the importance of moving beyond traditional inundation assessments toward more comprehensive evaluations of systemic risk. Meanwhile, storyline approaches and tools such as the CIRCLE method have been applied to evaluate critical infrastructure vulnerability in Cork City (de Bruijn et al., 2016), yet integration with compound flood hazard models is still in its infancy. The recent emergence of unconventional approaches, including audio-based flood risk exploration (Scriven, 2020), highlights a growing interest in integrating social engagement and communication into compound flood modelling. Given the projected intensification of CoMF, future research must prioritise coupled hazard–vulnerability frameworks and assess how systemic inequities shape differential exposure and impacts across CHC communities. Overall, flood modelling efforts pertaining to the CHC region reveal rapid methodological innovation toward multi-scale, multivariate, and computationally efficient systems capable of representing compound flood dynamics. High-resolution hydrodynamics remain essential for physical realism; statistical–hydrodynamic models provide probabilistic insight and scenario breadth; and emerging ML-hydrodynamic hybrids offer transformative potential for real-time forecasting. To support climate adaptation in



Cork Harbour and catchment, the next generation of modelling frameworks must integrate these strands within a holistic, risk-based decision-support system that captures both hydro-climatic complexity and socio-economic vulnerability.

3.3. Flood risk management and climate adaptation strategies

615 Flood risk management (FRM) and adaptation strategies have become central to addressing the multi-dimensional and evolving nature of compound flood hazards in Cork Harbour and its wider catchments. The FRM and adaptation strategies comprise structural, non-structural, and hybrid measures (Collier & Bourke, 2020; Langendijk et al., 2025; O'Mahony et al., 2020; O'Neill, 2018; OKRA, 2022).

3.3.1 Structural measures

620 Structural engineering interventions remain the cornerstone of FRM within CHC, reflecting a long-standing reliance on engineered flood protection to address the recurrent exposure of Cork City and surrounding estuarine communities to fluvial and coastal flooding (Jeffers, 2011). The reviewed literature indicates that these measures have evolved in response to increasing recognition of the complex interactions between fluvial, pluvial, tidal, and coastal processes that characterise flood risk within the estuarine environment of Cork Harbour. Major flood events, particularly the November 2009 flood, acted as
625 critical catalysts for investment in structural protection and accelerated the integration of flood risk considerations into urban planning and infrastructure development (Jeffers, 2011).

The flagship structural intervention identified in the literature is the Lower Lee Flood Relief Scheme (LLFRS), developed under the national Catchment Flood Risk Assessment and Management (CFRAM) Programme and incorporated within the
630 Flood Risk Management Plan for the Lee, Cork Harbour and Youghal Bay River Basin (OPW, 2018). LLFRS is a multi-component, state-led flood protection programme that constitutes the most extensive structural engineering investment in Ireland's flood-defence portfolio, providing the foundation for contemporary flood risk management in Cork City and addressing both fluvial and tidal flood hazards (CAAS Ltd, 2021; OPW, 2018, 2019). The scheme comprises a combination of flood walls, embankments, demountable barriers, pumping stations, drainage improvements, and modifications to flow
635 conveyance pathways designed to reduce the risk posed by both tidal and fluvial flooding. The review reveals that these measures represent a departure from traditional single-hazard engineering responses by explicitly recognising the compound nature of flood risk in Cork City and the wider harbour system.

The literature consistently demonstrates that structural adaptation remains necessary due to the concentration of population,
640 critical infrastructure, economic assets, and cultural heritage within low-lying areas of Cork City and the estuarine corridor (CAAS Ltd, 2021; OPW, 2018, 2025). Strategic Flood Risk Assessments undertaken for the Cork City Development Plan identify substantial areas exposed to present (CAAS Ltd, 2021) and future flood hazards (Kirkpatrick et al., 2020; Kirkpatrick



645 & Olbert, 2020), reinforcing the importance of engineered protection where relocation or land-use change is impractical (CAAS Ltd, 2021). Within this context, structural measures are viewed as essential for safeguarding existing urban functions and supporting continued socioeconomic development.

650 However, the reviewed studies also reveal increasing scrutiny of purely engineering-based approaches for flood risk management. The proposed flood-defence schemes in Cork City, particularly the LLFRS, generated substantial public debate concerning the social, cultural, and environmental implications of large-scale flood infrastructure. The widely documented Save Cork City campaign highlighted concerns regarding visual impacts, potential effects on the historic urban landscape, and the perceived prioritisation of technical protection objectives over community values and local identity (Jeffers, 2017; Jeffers, 2019). These debates exposed deeper tensions between expert-led risk assessments and local understandings of place, heritage, and urban futures, illustrating a broader shift in flood-risk governance from technical optimisation towards more socially informed and participatory approaches to adaptation planning (Jeffers, 2017; Jeffers, 2019).

655 Beyond these governance challenges, the literature questions the long-term sustainability of relying predominantly on structural interventions in the context of climate change. Although engineered schemes provide high levels of protection, they are capital-intensive, require long implementation periods, and may be less effective under conditions of sea-level rise, hydrological non-stationarity, and increasingly complex compound flood interactions. In particular, residual risks associated with coincident coastal and fluvial flooding may exceed assumptions embedded within historical design standards. Consequently, several authors argue that Cork's traditional reliance on structural measures reinforces a technocratic and hazard-centred paradigm that tends to underrepresent socio-economic vulnerability, cultural heritage, and broader dimensions of urban resilience (Jeffers, 2011, 2013, 2019). While the LLFRS has substantially enhanced Cork City's flood-defence capacity, engineered protection alone is unlikely to manage the escalating and non-linear risks posed by compound coastal-fluvial flooding, whose magnitude and frequency are expected to increase under conditions of climate change, sea-level rise, and hydrological uncertainty. A growing body of research and policy guidance highlights the need to move beyond conventional structural defence-based approaches towards hybrid, adaptive, and socially embedded flood risk management frameworks that combine engineering interventions, nature-based solutions, integrated coastal and catchment management, and dynamic adaptation pathways to support long-term climate-resilient development (Collier & Bourke, 2020; Langendijk et al., 2025; O'Mahony et al., 2020; O'Neill, 2018; OKRA, 2022).

3.3.2 Non-structural measures

Non-structural FRM and adaptation measures in CHC encompass a diverse suite of policy, governance, planning, behavioural, ecological, and institutional domains, and function as essential complements to traditional engineering structural solutions, where CoMF arises from interacting fluvial, pluvial, and coastal drivers (Collier & Bourke, 2020; Langendijk et al., 2025;



675 O'Mahony et al., 2020; O'Neill, 2018; OKRA, 2022). Synthesising the evidence from the Systematic Literature Review, the material in this section converges on a set of recurring non-structural responses that address preparedness, coordination, and adaptive capacity. From this, five interrelated domains of non-structural FRM and adaptation can be identified as defining the current approach in CHC. These domains recur across multiple studies and reports, albeit with varying emphasis and levels of implementation. They include: (i) integrated coastal and catchment management, (ii) flood forecasting and early warning
680 systems, (iii) integrated governance, (iv) stakeholder engagement, and (v) Nature-based Solutions. All of these have some degree of policy basis and support, a discussion of which is beyond the scope of this paper, but equally there is significant potential for greater implementation.

3.3.2.1 Integrated coastal and catchment management

Integrated Coastal Management (ICM) was previously identified as one of the most promising non-structural strategies for
685 addressing coastal erosion, flooding, and climate related risks characterized by land-sea interaction in Ireland (O'Mahony et al., 2014; Stori et al., 2023). Cork County Council were previously partners in several EU projects focused on implementing integrated coastal management in the wider county but also within the Cork Harbour area. The current County Development Plan 2020 (Cork County Council, 2022) maintains a commitment to supporting the application of integrated coastal management “in appropriate coastal zones throughout the County including Cork Harbour” (Cork County Council, 2022).
690 Whilst ICM, as a multidisciplinary approach, has the potential to bring together stakeholders, local authorities, and national bodies to manage coastal resources sustainably (O'Mahony et al., 2014) there is no national integrated coastal management policy limiting wider implementation of this approach. The relatively recent National Marine Planning Framework (NMPF) (O'Mahony et al., 2014) seeks to deliver Maritime Spatial Planning (MSP) for Ireland's maritime area. The NMPF recognises the impacts of climate change on Ireland's coast, outlines the various bodies that work on erosion and flood management and
695 highlights the role of climate adaptation in addressing those challenges but as it covers the maritime area from the mean high water seaward to in excess of 200 nautical miles it is not wholly suitable for addressing compound flooding. The Cork County Development Plan 2022 acknowledges the lack of integration between regulatory bodies that control activities in the coastal zone as a key issue facing the county (Cork County Council, 2022). The result is that management of issues like CoMF are addressed in a fragmented way across numerous policies including planning, environmental protection, flood risk management,
700 and marine regulation, with limited integration.

Earlier evidence from across Ireland shows that local authorities operate within a complex hierarchical system in which supranational (EU level), national, and local policy frameworks interact, though not always coherently (Flannery et al., 2015). Consistent with broader findings in the systematic literature review regarding the challenges of translating national and EU
705 level flood and coastal policy into local planning practice, Flannery et al. (2015) found that statutory development plans often struggle to operationalise meaningful flood and coastal risk mitigation measures, despite strong strategic guidance at higher



governance levels. In 2020, the Government created an Inter-Departmental Group (IDG) to scope out and oversee the development of a national coastal change management strategy with their findings published in 2023 (Government of Ireland, 2023). The IDG focused on the risks associated with coastal erosion, accretion and the displacement of the inter-tidal zone, not the risks from coastal flooding, with the report noting explicitly that existing arrangements are already in place to deal with these, so it does not come within the remit of the group. Accordingly, it is not considered in further detail here.

In parallel, substantial efforts have gone into adaptation to climate change at national and local levels. Central to this landscape is Ireland's National Adaptation Framework (NAF), which provides the overarching statutory framework for climate adaptation across sectors and administrative levels, including explicit recognition of flooding and coastal change as priority climate risks (DECC, 2024). The NAF establishes requirements for sector specific and local adaptation planning, thereby shaping the non-structural adaptation context within which flood risk is addressed. At the local scale, the literature highlights the role of Local Authority Climate Change Adaptation Strategies, developed in accordance with national guidance, as a key mechanism for translating national adaptation objectives into place-based action. These strategies explicitly identify flooding, including fluvial, coastal, and pluvial flooding, as a major climate risk, and emphasise preparedness, land use planning, emergency response, and cross-departmental coordination as core non-structural adaptation measures. Studies reviewing local implementation note that while these strategies strengthen awareness and institutional capacity, their effectiveness for CoMF depends on alignment with catchment scale flood risk management and coastal governance frameworks (Jeffers, 2017; Jeffers, 2020; Jeffers, 2022). Governance challenges persist: climate adaptation at the land-sea interface is hindered by policy incoherence, where sectoral plans for marine spatial planning, development control, coastal protection, and climate action often operate in parallel rather than in an integrated manner (Smith et al., 2022). Evidence from Youghal, a coastal town in east Cork, demonstrates how misalignment between local and national strategies can generate regulatory uncertainty, fragmented decision-making, and, in some cases, maladaptive outcomes (Smith et al., 2022).

A similar dynamic is observed in Cork Harbour, although in a more nuanced form. ICM-informed initiatives, most notably the Integrated Harbour Management Strategy, did contribute to raising awareness of cross-sectoral interactions and remain referenced in statutory plans such as the County Development Plans and Local Area Plans (COREPOINT, 2008; O'Mahony et al., 2020). In this sense, ICM has played an important role in shaping governance discourse and embedding the principle of integrated management within planning frameworks. However, consistent with observations elsewhere in Ireland, these advances have not translated into a substantive transformation of planning and decision-making practices on the ground. In particular, management of compound flood risk, encompassing the interaction between coastal, fluvial, and pluvial processes, remains only partially embedded within zoning decisions, development management processes, and coastal planning controls. Though ICM initially strengthened the governance culture and improved cross-sectoral dialogue in Cork Harbour, its influence has been more incremental than transformative, with integration often remaining procedural rather than fully functional, attributable in part perhaps to the lack of a solid national policy basis. This gap between strategic intent and implementation



reflects enduring institutional fragmentation, limited statutory backing, and the absence of clearly defined mechanisms for translating integrated risk assessments into enforceable planning outcomes.

745 Whilst there are several policies that recognise the challenges presented by a changing climate and coastal change and advocate for adaptation and coordination, the evidence suggests that the practical integration of compound flood considerations into core planning and regulatory systems remains uneven, with each policy area often being advanced separately. Addressing this implementation deficit will require not only stronger cross-sectoral coordination among statutory bodies operating within the harbour and its wider catchment, but also the development of actionable policies and related instruments and long-term monitoring frameworks. This pattern extends to Cork Harbour, where Integrated Coastal Management acted as an initial stimulus for assembling actors and discussing issues over a set period. There remains a need to further institutionalise compound flood considerations into zoning, development control, coastal planning and decision-making. Practical implementation of management measures remains ad hoc, with a need for an integrated management framework that can incorporate all the aspects of compound flooding. Achieving climate-resilient compound flood management will require a commitment to more integrated management, which is also dependent on broader structural reforms at national level. Within 755 Cork Harbour and catchment this is particularly critical coupled with the need for as long-term monitoring infrastructure.

3.3.2.2 Flood forecasting and early warning systems

Emergency planning and early-warning systems form a key dimension of non-structural FRM but remain underdeveloped in Cork Harbour. Although hydrodynamic modelling and national Catchment-based Flood Risk Assessment and Management (CFRAM) hazard maps have improved flood modelling capacity, there continue to be weaknesses in emergency and early 760 warning systems. For example, during the November 2009 flood, a state of emergency was declared in Cork City due to the scale of flooding and impacts on the city and surrounding hinterland (de Bruijn et al., 2016). The event exposed significant limitations in Cork City's emergency systems' architecture, particularly the delayed and fragmented communication of meteorological and hydrological forecasts, which contributed to the severity of the impacts experienced (de Bruijn et al., 2016; 765 Jeffers, 2011).

In response, considerable progress has been made at both national and local levels to strengthen flood forecasting and warning capabilities. At the national scale, the OPW, in partnership with Met Éireann, has advanced the Flood Forecasting and Warning Service (FFWS), which aims to deliver more integrated, timely, and impact-based flood warnings by linking meteorological, 770 hydrological, and coastal data streams. This represents a significant shift towards a more coordinated and anticipatory early warning framework, consistent with broader objectives under Ireland's flood risk management and climate adaptation policies. While ongoing national efforts led by Met Éireann to refine the existing 'red-orange-yellow' warning system, through the development of more spatially targeted and impact-based alerts, represent a significant step towards improving the relevance



775 and usability of warnings at local scales, these enhancements are still in progress and have yet to fully address the complexities associated with compound flood dynamics.

At the local level, Cork County Council operates a free text message service that warns people about severe weather events including floods, but it is an opt-in service which may impact upon uptake levels (County Council, 2026). This initiative reflects a practical effort to enhance risk communication and public preparedness, complementing national-scale forecasting systems by translating warnings into locally relevant information. However, as an opt-in service, its effectiveness is inherently dependent on user registration and engagement, which may constrain its reach and limit accessibility among vulnerable or hard-to-reach populations. Without such advances, the CHC region's early warning capabilities remain mismatched to the emergent compound flood hazard landscape.

785 Despite these advancements, challenges remain in achieving a fully integrated early warning system capable of addressing compound flood risk. In particular, the need to ensure seamless coordination between national forecasting services (e.g., FFWS), local dissemination mechanisms (e.g., MapAlert), and emergency response structures is critical. Furthermore, while improvements in forecasting accuracy and lead times are evident, translating warnings into effective, timely action at the household and community scale remains an ongoing challenge. This is especially pertinent in the context of compound flooding, where interacting coastal, fluvial, and pluvial processes can complicate hazard characterisation and communication. Overall, while post-2009 developments demonstrate meaningful progress towards a more coherent and multi-layered early warning architecture, further efforts are required to enhance system integration, expand accessibility, and ensure that advances in forecasting are matched by equally robust communication and response mechanisms within the Cork Harbour context.

795 3.3.2.3 Integrated governance

Flood governance in the CHC is characterised by fragmentation, sectoral silos, and an enduring reliance on engineering-centric paradigms. Early analyses by Jeffers (Jeffers, 2011, 2014) highlight that Irish flood policy remains dominated by engineering-centric paradigms, neglecting socio-economic vulnerability, cultural values, and environmental histories. This technocratic framing reduces the effectiveness of hazard governance by obscuring the socio-political dimensions of flood risk. Recent studies have reinforced these limitations, particularly the flood governance challenges reflected in conflicts around the LLFRS (Jeffers, 2022). Through analyses of the Cork City flood-defence dispute, Jeffers (Jeffers, 2019, 2022) characterises the situation as a “dispute” due to the sustained and multi-dimensional contestation surrounding proposed flood defence measures. Specifically, differing place attachments, competing risk framings, and divergent socio-cultural values among stakeholders have generated persistent public opposition and debate. This has extended beyond technical disagreements to encompass broader questions of heritage, landscape identity, and the acceptable trade-offs between protection and place transformation. Jeffers (2022) argues that building broader “constituencies of interest,” rather than relying on narrow consultative models, may provide a more democratic foundation for flood governance.



O'Neill demonstrated that, despite a clear shift in national policy rhetoric towards integrated FRM, implementation has historically remained dominated by physical and technological interventions (O'Neill, 2018), with comparatively limited emphasis on institutional coordination or the incorporation of local context. These frameworks explicitly promote coordination across policy domains, alignment with spatial planning, and the incorporation of climate adaptation principles into decision-making processes. Medway et al (Medway et al., 2022) also identified deficits in aligning disaster risk reduction (DRR) and climate-change adaptation (CCA) across Ireland, proposing six strategic pathways to better align policy and practice. However, the persistent misalignment between planning legislation and FRM objectives (Revez et al., 2017), combined with conflicting narratives of heritage, urban futures, and risk (Jeffers, 2019, 2022), continues to hinder effective, equitable adaptation. This reviewed literature indicates that flood governance integration in CHC remains partial and uneven, constrained by institutional fragmentation, technocratic orientations, and insufficient incorporation of social vulnerability considerations. At the same time, recent national policy frameworks, including the Catchment-based Flood Risk Assessment and Management (CFRAM) Programme, the Flood Risk Management Sectoral Adaptation Plan (OPW, 2025) and the Report of the Inter-Departmental Group on the National Coastal Change Management Strategy (Government of Ireland, 2023), demonstrate an explicit strategic commitment to more integrated, cross-sectoral, and climate-responsive flood governance. These documents collectively emphasise improved policy alignment, enhanced institutional coordination, the integration of climate adaptation into spatial planning, and the adoption of nature-based and participatory approaches to risk management. Despite this progressive policy landscape, evidence suggests that the translation of these high-level commitments into consistent operational practice remains incomplete. As such, achieving effective compound flood governance in Cork Harbour will require a more substantive paradigm shift: one that moves beyond strategic intent towards the practical embedding of multi-actor coordination, socio-environmental insights, and participatory governance processes within decision-making frameworks, ensuring that national policy ambitions are realised at the local and catchment scales.

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3.3.2.4 Stakeholder engagement

Stakeholder engagement is essential for meaningful and legitimate FRM in CHC but remains inadequately institutionalised. Across the literature, stakeholder engagement deficits are repeatedly identified as central drivers of policy conflict, diminished institutional legitimacy, and barriers to transformative climate adaptation. An analysis of the "Save Cork City" campaign, which opposed the LLFRS (Jeffers, 2017; Jeffers, 2020; Jeffers, 2019), revealed structural weaknesses in participatory governance including insufficient consultation, lack of transparency, and overlooked cultural and heritage values (Jeffers, 2019). The study revealed public scepticism towards flood defence strategies, and highlighted deficiencies in stakeholder consultation processes. Jeffers (2019) expanded on this by employing a frame analysis to examine competing narratives surrounding the Cork flood relief dispute, demonstrating how place attachment and conflicting discourses shape public opposition and governance challenges. Jeffers (2020) goes further to argue that failures in public participation not only undermine specific flood-mitigation projects but also create new and durable barriers to transformative adaptation. He

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concluded that incremental adjustments to consultation processes are insufficient. Instead, achieving meaningful participatory adaptation will require system-wide reform of hazard governance, underpinned by enhanced resourcing, strengthened institutional capacity, and a demonstrated willingness to redistribute decision-making authority across a broader range of stakeholders.

In this regard, the Report of the Inter-Departmental Group on the National Coastal Change Management Strategy (Government of Ireland, 2023) provides an important policy foundation, explicitly advocating for more inclusive, transparent, and participatory approaches to coastal and flood risk management. Jeffers (2022) added a critical perspective by contrasting consultative and constituency-building approaches to hazards governance. The analysis of the LLFRS dispute showed that while traditional consultations often fail to generate meaningful dialogue, conflict itself can catalyse broader public engagement, drawing new actors into debates on flood governance. This enlarging of stakeholder communities presents both challenges—due to divergent interests, priorities, and risk perceptions—and opportunities, as wider public mobilisation can exert pressure on institutions to adopt more inclusive, transparent, and socially legitimate governance models. In the Cork context, this dynamic is increasingly reflected in the role of participatory structures such as the Public Participation Network (PPN), which provides a formal mechanism for community and voluntary groups to engage with local authority decision-making processes. Through representation on strategic policy committees and consultation processes, the Cork PPN has the potential to amplify community perspectives, including those related to flood risk, climate adaptation, and local resilience.

Complementary studies highlight the potential of co-produced climate services, interdisciplinary methods, transformative adaptation, and virtual engagement tools to enhance social learning and public participation (Clarke, 2018; McCullagh et al., 2024). Clarke (2018) demonstrated that virtual reality tools, cultural valuation, and participatory scenario development can broaden engagement, democratise knowledge, and support transformative adaptation. McCullagh et al. (2024) illustrated how co-developed climate services in Cork City can improve local decision-making, strengthen citizen engagement, and embed climate knowledge within everyday governance practice. Their findings align with emerging research by Laino and Iglesias (2024) and McCullagh et al. (2025), who proposed multi-hazard risk frameworks that integrate exposure, sensitivity, and adaptive capacity indicators, offering participatory pathways for holistic adaptation planning and climate justice. While such approaches can broaden public engagement, enhance social learning, and support transformative adaptation, mainstreaming them requires institutional willingness to redistribute decision-making power, and embed public participation throughout the FRM process.

3.3.2.5 Nature based Solutions

Nature-based Solutions (NbS) are increasingly recognised as essential components of integrated catchment management, offer multiple co-benefits such as flood attenuation, biodiversity enhancement, and water-quality improvement (Bourke et al., 2022; Collier & Bourke, 2020; Heneghan et al., 2021; Molloy et al., 2024; Murphy, 2024). Despite their widely acknowledged



potential, NbS remain under-utilised and insufficiently embedded within the FRM portfolio of the CHC region. At the national scale, studies highlight the need to expand NbS adoption as part a more holistic, systems-based approach to integrated catchment management (for example, (Collier & Bourke, 2020) and (Molloy et al., 2024)), aligning with emerging policy priorities around climate resilience and ecosystem-based adaptation.

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At the catchment scale, empirical studies demonstrate the effectiveness of upstream NbS interventions, such as detention basins, woodland swales, and leaky dams, in reducing peak flows and improving water quality (Murphy, 2024). Meanwhile downstream, wetland restoration and managed realignment provide valuable flood-storage and ecological benefits (OKRA, 2022). For example, community-led restoration at Harper's Island wetlands underscores how multi-stakeholder collaboration
885 can expand habitat diversity (Verling et al., 2025). Similarly, at the urban fringe, the Marina Park Phase 2 project integrates NbS principles through wetland conservation, woodland enhancement, and stormwater storage in the Atlantic Pond, which functions as a key flood-attenuation and drainage asset for the South Docks area (OKRA, 2022). These examples demonstrate emerging but uneven progress in mainstreaming ecological functions into Cork City's flood-risk landscape.

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Recent policy developments further reinforce the importance of NbS within Ireland's adaptation agenda. The Report of the Inter-Departmental Group on the National Coastal Change Management Strategy (Government of Ireland, 2023) explicitly identifies NbS as a key component of sustainable coastal adaptation, promoting measures such as managed realignment, restoration of coastal wetlands, and the integration of blue-green infrastructure into planning frameworks. Similarly, the Flood Risk Management Sectoral Adaptation Plan (OPW, 2025) emphasises the role of NbS in complementing traditional engineered
895 defences and advancing low-regret, flexible adaptation pathways. These priorities align closely with the EU Green Deal (Fetting, 2020), which advocates for ecosystem-based adaptation, large-scale habitat restoration, and the integration of blue-green infrastructure into climate resilience planning. The River Basin Management Service (formerly the Local Authority Waters programme, LAWPRO) together with the Department of Housing, Local Government and Heritage (DHLGH) have worked collaboratively to develop an interim guidance document on nature-based solutions to the management of rainwater
900 and surface water runoff in urban areas (Government of Ireland, 2022). The interim guidance sets out the steps to be taken to ensure that all urban interventions or projects incorporate water sensitive urban design and manage rainwater in a nature-based and sustainable manner and in that way improve water quality, reduce the impacts of climate change and reduce the risks from urban flooding by retaining more rainfall.

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Despite this strong policy support, NbS implementation in the CHC remains fragmented and largely project-based, constrained by governance silos, land availability, and limited statutory integration. Scaling NbS will therefore require their systematic incorporation into CFRAM processes and spatial planning, alongside robust monitoring frameworks and stronger institutional coordination. Without such integration, the potential of NbS to support a coherent, catchment-scale response CoMF will remain only partially realised.



910 3.3.3 Hybrid measures

Hybrid FRM, the strategic integration of structural and non-structural measures has emerged as a promising approach in Ireland (O'Neill, 2018), which has implications for addressing the CHC region's compound flood risk profile. The literature consistently demonstrates that neither hard engineering interventions nor soft governance or ecological measures alone are sufficient to confront the scale, complexity, uncertainty and interactions between fluvial, pluvial, groundwater, tidal and storm-surge drivers. Instead, hybrid interventions offer a combinatory resilience advantage: blending the reliability of engineered protections with the flexibility, co-benefits, and adaptive capacity inherent to ecological and governance-based approaches (O'Neill, 2018; OKRA, 2022). Evidence from Cork Harbour highlights both the need and the potential for such hybridisation. On the structural side, the LLFRS anchors Cork City's current FRM portfolio, providing engineered protection against both tidal and fluvial risk flood (CAAS Ltd, 2021; OPW, 2018, 2019). They are expensive, inflexible, socially contested, and vulnerable to overtopping under extreme compound scenarios (Jeffers, 2017; Jeffers, 2011, 2013, 2019). These limitations underscore the imperative for complementary strategies that extend beyond hard infrastructure.

NbS could play an essential complementary role within hybrid portfolios (Bourke et al., 2022; Murphy, 2024). Studies in the Lee and Glashagarriff catchments demonstrate that detention basins, woodland swales, boulder weirs, and leaky dams can attenuate peak flows and also improve water quality, contributing to flood mitigation while delivering ecological co-benefits (Bourke et al., 2022; Murphy, 2024). Downstream, wetland restoration, managed realignment, and urban greening (e.g., Marina Park Phase 2) enhance flood storage capacity while providing biodiversity and amenity co-benefit portfolios (Bourke et al., 2022; Murphy, 2024; OKRA, 2022; Verling et al., 2025). Nonetheless, NbS require long-term monitoring, appropriate land availability, and integration into statutory planning to avoid maladaptation.

Hybrid approaches can also benefit from the use of non-structural governance tools such as ICM coordination, multi-hazard early-warning systems, land-use planning controls, and participatory decision-making to bridge jurisdictional and institutional gaps. In this context, integrated management, drawing on the core principles of ICZM, offers a valuable framework for linking terrestrial and marine planning, aligning hazard governance across sectors, and enhancing community engagement. However, while these integrative principles have been increasingly recognised within policy and practice in CHC, their full potential remains only partially realised, with implementation often constrained by institutional fragmentation and uneven cross-sectoral coordination (O'Mahony et al., 2020; Smith et al., 2022). Integrating these governance mechanisms with engineered and ecological measures can enhance adaptive pathways planning, enabling long-term, and flexible strategies consistent with Climate Resilient Development Pathways (Langendijk et al., 2025), which seek to account for the interactions between adaptation, mitigation, sustainable development and justice over time and against a backdrop of uncertainty (Langendijk et al., 2025).



4. Discussion

This systematic review provides the first comprehensive synthesis of compound flood dynamics, modelling practices, management and governance approaches, and climate-change adaptation strategies for CHC, and in doing so delivers insights that extend far beyond the Irish context. The findings have substantive implications for the international flood risk, coastal adaptation, and compound-event communities, particularly as coastal–estuarine catchments worldwide confront increasingly complex hydrodynamic interactions under anthropogenic climate change. The insights emerging from Cork Harbour and Catchment offer transferable lessons to coastal and estuarine catchments worldwide, particularly those grappling with multi-driver flooding, governance fragmentation, and the need to design hybrid, climate-resilient adaptation pathways under deep uncertainty. The insights are structured around five interlinked themes: (i) CHC as an internationally relevant microcosm of CoMF; (ii) methodological advances in compound-flood modelling; (iii) governance and social dimensions; (iv) nature-based and hybrid adaptation strategies; and (v) global implications and contributions of this work.

4.1 CHC as an internationally relevant land-sea laboratory for CoMF

CHC emerges from this review as a potentially important land–sea “natural laboratory” for compound flood research. Its flood regime is shaped by simultaneous or sequential interactions of fluvial peaks, pluvial runoff, tidal fluctuations, storm surges, coastal water-level anomalies, and rising mean sea levels (Comer et al., 2017; Kirkpatrick et al., 2020; Kirkpatrick & Olbert, 2020; Nash et al., 2018; Olbert et al., 2017). This multi-driver configuration reflects precisely the compound-event dynamics identified globally as the most consequential and least understood in contemporary flood science (Bevacqua et al., 2017; Bevacqua et al., 2019; Wahl et al., 2015; Zscheischler et al., 2020; Zscheischler et al., 2018). Evidence compiled across the climatic, hydrological, and coastal studies demonstrates that CHC is undergoing a systematic transition from a historically fluvial-dominated regime toward one increasingly shaped by coastal-amplification, driven by rising mean sea levels (~40 cm since the 1840s), enhanced surge behaviour, and intensified tidal interactions (Kirkpatrick et al., 2020; Kirkpatrick & Olbert, 2020). Under high-end sea-level-rise scenarios, coastal inundation could increase by up to 400%, while spring-tide flooding may become a bi-monthly occurrence independent of surge conditions (Kirkpatrick et al., 2020; Kirkpatrick & Olbert, 2020). These shifts coincide with projected 20–30% increases in heavy rainfall during winter and autumn (Nolan, 2015; Nolan & Flanagan, 2020; Nolan et al., 2017) and substantial observed increases in winter and spring river flows (Moradian et al., 2023; Murphy et al., 2023), creating conditions for non-linear hazard amplification that challenge traditional single-driver risk modelling and governance frameworks.

The compound-flood dynamics observed in CHC are not unique to Ireland but reflect patterns documented in mid-latitude estuaries including in the Netherlands coastal areas (Philipp Heinrich et al., 2023b; P. Heinrich et al., 2023; Sebastian, 2022), UK coasts (Hendry et al., 2019), US Coasts (Ghanbari et al., 2021; Sohrabi et al., 2025) and several other coastal areas globally, where intensified precipitation, rising sea levels, and storm-surge regimes interact to produce disproportionately severe impacts



(Bevacqua et al., 2017; Bevacqua et al., 2019; Wahl et al., 2015; Zscheischler et al., 2020; Zscheischler et al., 2018). Within this global context, CHC provides a controlled, data-rich natural laboratory in which theories of compound flood generation, multivariate dependence, complex hydrodynamic interactions, long-term hindcasting, and multi-scenario hazard amplification can be empirically tested and refined. By studying CHC as a representative land–sea system, this paper offers a clear, real-world demonstration of how CoMF manifests in constrained estuarine cities where riverine and coastal processes continuously interact. The insights emerging from the CHC case study resonate strongly with international contexts characterised by complex estuarine or coastal–urban systems exposed to compound flooding. In this regard, cities such as Rotterdam, New York, Shanghai, Hamburg, and Brisbane are referenced as illustrative comparators due to their shared exposure to interacting fluvial, coastal, and pluvial flood drivers, as well as their prominence within the international literature on integrated and adaptive flood risk management. These cases have been widely studied as leading examples of efforts to address compound flood risk through a combination of engineered defences, nature-based solutions, and governance innovation, thereby providing a relevant basis for situating the Cork Harbour findings within a broader global context. Collectively, the findings position CHC as a globally relevant analogue for coastal and estuarine regions undergoing climate-driven transitions, providing critical understanding of how atmospheric, terrestrial, and oceanic processes co-produce compound flood risk in a warming world and the need for these to be managed in an integrated and adaptive way.

4.2 Methodological advances in compound flood modelling

Beyond contextual insights, this review highlights methodological advances that are directly transferable to other coastal and estuarine systems. The past decade has seen considerable progress in CoMF modelling in CHC, particularly through multi-scale nested hydrodynamic models, coupled statistical–hydrodynamic hybrids, and machine-learning–based surrogates (Bevacqua et al., 2017; Bevacqua et al., 2019; Wahl et al., 2015; Zscheischler et al., 2020; Zscheischler et al., 2018). The MSN_Flood hydrodynamic system, with its telescoping spatial resolution from 90 m at harbour scale to 2 m in dense urban grids (Comer et al., 2017; Nash et al., 2018; Olbert et al., 2017), exemplifies how multi-scale models can capture the hydrodynamic transitions and feedbacks central to compound floods. Its successful application to Cork city and the River Lee catchment demonstrates the feasibility of integrating coastal, fluvial, and pluvial processes into a single modelling architecture. The Cork Harbour and Catchment case thus demonstrates that multi-driver, multi-scale hydrodynamics are increasingly feasible for mid-sized coastal cities, not only mega deltas.

An equally important contribution of the Cork Harbour case is the development of a multivariate statistical–hydrodynamic framework that advances compound-flood modelling beyond single-driver approaches. The framework introduced by Olbert et al. (Olbert et al., 2023) explicitly quantifies dependence between surge residuals, tidal states, and river flows using copulas and joint exceedance probabilities, and then propagates these multivariate scenarios through full hydrodynamic simulations. This eight-step dependency–inundation methodology integrates extreme-value analysis, joint-probability modelling, and hydrodynamic inundation mapping into a coherent workflow that captures the true multivariate structure of compound flood



1010 hazards (Olbert et al., 2023). Such coupled statistical–hydrodynamic systems provide decision-makers with physically credible
scenario portfolios that reflect real-world driver interactions rather than artificially isolated extremes. By coupling
joint-probability climatologies with physics-based inundation modelling, the Cork framework represents a state-of-the-art
approach to compound-flood assessment and offers a transferrable template for coastal–urban estuaries globally, where similar
interactions between fluvial, pluvial, and coastal processes shape flood risk.

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This paper further demonstrates the promise of artificial intelligence and physics-informed AI modelling for faster compound-
flood prediction (Moradian et al., 2024; Olbert & Moradian, 2024). These hybrid modelling pathways can help bridge
computational bottlenecks that limit the operational use of high-resolution hydrodynamic models. Internationally, such
approaches can underpin early-warning systems in regions lacking computational resources to run expensive high-resolution
1020 hydrodynamics or where real-time forecasting is essential. The Cork approach—hydrodynamics for training and ML for
forecasting—provides a scalable pathway for estuarine-coastal catchments in low-resource settings, including densely
populated Asian deltas, the Caribbean, and West Africa. These hybrid modelling approaches can support rapid scenario
generation, dynamic early warning, and data-driven decision support. Several important limitations remain. Existing models
do not integrate groundwater–surface interactions, urban drainage networks, or multi-driver uncertainty quantification.
1025 Hydrodynamic models, though physically robust, require high computational resources and intensive calibration. Traditional
ML models struggle with extrapolation beyond historical data—problematic given future climate non-stationarity. For
example, studies by Moradian et al. (2024) show that Machine Learning surrogates (especially Radial Basis Function models)
can approximate hydrodynamic outputs with substantial computational savings. However, the absence of deep learning
enhanced integrated compound flood models capable of coupling rainfall, runoff, tides, surges, waves, and urban drainage
1030 remains a critical research gap. Deep learning (DL) and hybrid DL–hydrodynamic frameworks offer new opportunities for
near real-time flood forecasting.

4.3 Governance and social dimensions: fragmentation, contestation, and adaptive capacity

A critical insight emerging from Cork Harbour is that CoMF is not only a hydrological challenge but also presents governance
and social legitimacy challenges. This paper reveals flood risk governance in CHC is characterised by sectoral silos,
1035 institutional fragmentation, misaligned spatial planning, and public objection (Jeffers, 2011, 2019, 2022; McDermott &
Surminski, 2018). These patterns of flood risk governance challenges are widely documented across Europe (Alexander et al.,
2016; de Boer et al., 2025; Mees et al., 2014; Wiering et al., 2017) and in the USA (Tullos, 2018; Tyler et al., 2019),
demonstrating that the governance issues identified in CHC mirrors the challenges experienced elsewhere. The Cork flood-
defence controversy, centred on the public dispute over the LLFRS, illustrates the consequences of technocratic decision-
1040 making that prioritises engineered solutions while insufficiently engaging with community values, heritage, socio-cultural
attachments, and perceived fairness (Jeffers, 2017; Jeffers, 2019, 2022). This echoes international experiences, such as



Hurricane Katrina and the 2005 Great Flood of New Orleans (Cigler, 2007) and other initiatives globally, where infrastructural decisions became socially contested because they inadequately addressed local narratives of place, identity, and justice.

1045 The Cork city case therefore contributes an internationally important demonstration of how place attachment, environmental
identity, and procedural justice shape adaptation outcomes. Compound-flood adaptation must be embedded in participatory,
socially legitimate, and equity-informed governance frameworks, particularly where historical grievances and uneven exposure
amplify vulnerability (McDermott & Surminski, 2018; Revez et al., 2017). Cork Harbour demonstrates the importance of
building broad constituencies of interest, leveraging co-produced climate services, and transitioning beyond minimal
1050 consultation toward meaningful shared decision-making (Clarke, 2018; Clarke & Murphy, 2019; Clarke et al., 2016, 2018;
McCullagh et al., 2024). This reinforces broader global insights that flood risk governance cannot succeed without synergy
and local coordination in flood management, institutional transformation, narrowing down public–private divide, societal
resilience demonstrated via efficiency and legitimacy (e.g. accountability and public participation), public participation,
community engagement in the flood planning and recovery processes, considering socially vulnerable populations, and social
1055 equity-centred governance (Alexander et al., 2016; de Boer et al., 2025; Meerow et al., 2019; Mees et al., 2014; Tullos, 2018;
Tyler et al., 2019; Wiering et al., 2017).

4.4 Compound flood risk management and climate adaptation strategies

Evidence from CHC strongly reinforces the global consensus that neither structural measures nor NbS alone can deliver robust
1060 resilience under climate uncertainty. Although NbS in CHC remain under-utilised relative to their ecological potential,
empirical results from upstream catchments, such as the performance of detention basins, woodland swales, leaky dams, and
wetland systems (Murphy, 2024), align closely with international findings that hybrid green–grey portfolios outperform
standalone structural interventions (Alves et al., 2019; Azhar et al., 2025; Du et al., 2020; Kapetas & Fenner, 2020). In practice,
CHC’s emerging adaptation mix, including modular structural flood relief schemes (CAAS Ltd, 2021; de Bruijn et al., 2016),
1065 NbS deployment in upstream catchments (Murphy, 2024), wetland restoration (Doran & O’Higgins, 2020), and multifunctional
public-realm interventions such as Marina Park Phase 2 (OKRA, 2022) offers a globally replicable model of compound-flood
management that integrates engineering reliability with ecological integrity. These insights underscore a central lesson: NbS
realise their full value only when embedded within carefully designed hybrid portfolios, supported by long-term monitoring
and adaptive governance rather than implemented as symbolic or isolated alternatives.

1070 4.4.1 Structural Flood Risk Management (FRM)

Cork’s FRM has historically been dominated by structural engineering interventions, most notably the LLFRS, the largest and
most technically sophisticated project of its kind in Ireland (CAAS Ltd, 2021; OPW, 2019). While structural defences provide
important near-term protection (CAAS Ltd, 2021; OPW, 2018, 2019), they face fundamental limitations in compound-flood



contexts. Firstly, designed around single-driver return periods, such systems are vulnerable to failure when multiple drivers co-occur, even if no individual driver exceeds its threshold. Secondly, the LLFRS dispute also highlights the socio-political fragility of structural solutions: conflicts over heritage, urban aesthetics, ecological values, and public trust demonstrate how engineered interventions can become highly contested and delay adaptation (Jeffers, 2017; Jeffers, 2020; Jeffers, 2019, 2022). Public opposition can stall or derail adaptation projects (Jeffers, 2017; Jeffers, 2019). Thirdly, structural defences risk inflexibility, land use lock-in, high capital costs, resource intensive and slow implementation, and reduced flexibility under climate uncertainty. Fourthly, rigid engineering structures can restrict future adaptation options, concentrate risk downstream, and degrade ecological connectivity, making them poorly suited to non-stationary climate futures. These limitations underline the need for Cork to transition toward modular, flexible, and multi-functional engineering designs that can be integrated within broader hybrid and adaptive FRM frameworks.

4.4.2. Non-structural and ecosystem-based measures

Flood forecasting and Cork city's emergency warning systems remain fragmented, with early-warning systems still largely single-driver despite the need for integrated forecasting of rainfall, tides, surges, and pluvial flows. Multi-hazard, probabilistic early-warning systems integrating real-time hydrometric, meteorological, and tide–surge data remain a critical gap. Non-structural FRM measures including ICM, flood forecasting and early-warning systems, emergency planning, and participatory governance are increasingly recognised as essential complements to structural defences. Early experiences with ICM in Cork improved cross-sector communication and local capacity-building (COREPOINT, 2008; O'Mahony et al., 2020), yet continued weak coordination of statutory mandates continues to impede integration across land-sea domain (Flannery et al., 2015; Smith et al., 2022). Flood forecasting and Cork City's emergency warning systems remain fragmented and predominantly single driver, despite growing evidence that compound flood hazards require probabilistic, multi-hazard, real-time decision support. Governance fragmentation persists as one of the most significant barriers to adaptation: Irish FRM remains constrained by siloed institutions, technocratic practices, and insufficient engagement with vulnerability, justice, and equity (Jeffers, 2011, 2014, 2019). The 2009 Cork flood exposed failures in institutional coordination and risk communication. The LLFRS case demonstrates how governance deficits can lead to public opposition and mistrust (Jeffers, 2017; Jeffers, 2019), ultimately slowing adaptation progress. Transformative adaptation in CHC will therefore require co-produced knowledge, more inclusive participatory structures, and recognition of the cultural and historical dimensions that shape risk perception and public acceptance (Clarke, 2018; Clarke et al., 2016; Jeffers, 2020; Jeffers, 2011, 2014).

NbS present an increasingly important pathway for compound-flood adaptation, with empirical evidence demonstrating their ability to attenuate peak flows, enhance water quality, restore biodiversity, and deliver multiple ecosystem services (Bourke et al., 2022; Doran & O'Higgins, 2020; Murphy, 2024; OKRA, 2022; Verling et al., 2025). In upstream agricultural sub-catchments, detention basins, leaky dams, woodland swales, and riparian wetlands have shown substantial potential to reduce hydrological flashiness and nutrient loads (Murphy, 2024). In downstream estuarine environments, wetland restoration



and managed realignment enhance flood storage (OKRA, 2022) while supporting habitat resilience. Yet despite these benefits, NbS remain under-institutionalised, hindered by land-use constraints, governance silos, lack of long-term monitoring, and limited incorporation into statutory planning, CFRAM design standards, or zoning regulations. International experience shows that NbS are most effective when strategically embedded within wider FRM portfolios rather than deployed as symbolic or isolated interventions. Their future success in CHC will depend on rigorous performance monitoring, cross-agency coordination, and long-horizon investment frameworks.

4.4.3. Hybrid and climate-resilient pathways

Hybrid FRM integrating structural, non-structural, and Nature-based measures offer an opportunity to overcome the limitations of purely structural or purely regulatory approaches. It represents the most promising direction for Cork Harbour's climate-resilient future. Empirical studies in Cork Harbour's both upper stream catchment and downstream coastal areas demonstrate the ability of NbS to reduce flood peaks, improve water quality, enhance biodiversity and ecosystem Services, and support rural livelihoods (Bourke et al., 2022; Doran & O'Higgins, 2020; Murphy, 2024; OKRA, 2022; Verling et al., 2025). Community-led biodiversity protection and restoration offer ecosystem Services and adaptive flood storage and habitat benefits (Doran & O'Higgins, 2020; Verling et al., 2025). International case studies also show that hybrid green–grey strategies outperform hard or soft approaches alone, delivering lower residual risk and higher benefit–cost performance (Alves et al., 2019; Azhar et al., 2025; Du et al., 2020; Kapetas & Fenner, 2020). In Cork Harbour, elements of hybridisation are emerging through LLFRS enhancements (OPW, 2018, 2019), Marina Park Phase 2 (OKRA, 2022), and ICZM initiatives (O'Mahony et al., 2020), yet full integration remains incomplete. A forward-looking framework for CHC is offered by Climate Resilient Development Pathways (CRDP), which emphasise modularity, sequencing of interventions, dynamic adaptation pathways, and explicit consideration of justice, governance coherence, and deep uncertainty (Langendijk et al., 2025). Embedding CRDP principles would allow CHC to transition from reactive, project-based management toward a flexible, learning-oriented, and socially legitimate adaptation system, aligning structural defences, NbS, and non-structural governance tools across multiple temporal and spatial scales.

4.5 Global implications and contributions of this work

By synthesising nearly three decades of multi-driver flood modelling, governance analysis, and adaptation practice in CHC, this review offers a set of globally transferable insights for the international compound-flood research community. First, the findings reaffirm that compound floods demand multivariate, physics-aware, and AI-enhanced modelling frameworks. Single-driver assessments consistently underestimate compound-flood risk because they overlook the nonlinear amplification that arises from the interaction of fluvial, pluvial, tidal, surge, and groundwater processes. Evidence from CHC shows that integrating joint-probability analysis with high-resolution, multi-scale hydrodynamics fundamentally reshapes hazard understanding—demonstrating the need for fully integrated, physics-informed models that unify extreme-value statistics, dynamic hydrodynamics, climate projections, and AI-accelerated computation. Such coupled, data-rich approaches provide a



1140 methodological blueprint for next-generation compound-flood forecasting and resilience planning globally. Second, CHC
illustrates that governance fragmentation remains a universal barrier: institutional silos, inconsistent policy signals, and
insufficient public engagement undermine even the most sophisticated technical solutions. The contested LLFRS process
mirrors similar conflicts worldwide, reinforcing that co-production, transparent risk communication, and social legitimacy are
prerequisites for effective adaptation. Third, CHC's experience underscores that hybrid green–grey strategies offer the most
1145 robust and adaptable pathway, aligning with the international literature on hybrid adaptation measures (Alves et al., 2019;
Azhar et al., 2025; Du et al., 2020; Kapetas & Fenner, 2020). Hybrid interventions—combining engineered reliability with
NbS, urban design, and adaptive management—outperform both hard-only and soft-only approaches, provided they are
supported by iterative governance and long-term monitoring.

4.6 Source-to-sea framework for compound flood resilience

1150 A central finding of this review is that research and practice relating to CoMF have evolved largely within separate domains
of flood modelling, risk management, and climate adaptation. While substantial progress has been made in each of these areas
individually, their development has often occurred in parallel rather than through coordinated integration. This fragmentation
is increasingly problematic as climate change accelerates the frequency, magnitude, and interdependence of flood-generating
processes across coastal-estuarine systems. The complexity of CoMF arises not only from interactions among fluvial, pluvial,
1155 groundwater, tidal, storm-surge, and sea-level-rise drivers, but also from interactions between physical processes, socio-
economic vulnerabilities, governance arrangements, and adaptation decisions. Addressing these challenges therefore requires
an integrative perspective capable of linking the source-to-sea continuum with the scientific, operational, and institutional
systems responsible for managing flood risk.

1160 To address this gap, we propose a Source-to-Sea Compound Flood Resilience Framework (Fig. 5), which conceptualises flood
resilience as an emergent property arising from the interaction of three interconnected intelligence layers operating across the
catchment–estuary–coast continuum: predictive intelligence, operational intelligence, and adaptive intelligence. The
framework builds upon a source-to-sea understanding of compound flooding, recognising that flood risk is generated through
the interaction of climatic drivers, hydrological responses, coastal processes, human systems, and adaptation interventions
1165 distributed across multiple spatial and temporal scales.

The foundation of the framework consists of the climatic and environmental drivers of compound flooding, including extreme
precipitation, river discharge, groundwater emergence, tides, storm surges, and sea-level rise. These drivers interact
dynamically throughout the source-to-sea continuum to generate compound flood hazards whose impacts frequently exceed
1170 those associated with individual drivers acting independently. Effective management of these hazards requires the first
intelligence layer: predictive intelligence. This layer encompasses hydrological and hydrodynamic modelling, multivariate



statistical dependence analysis, flood forecasting systems, remote sensing, climate projections, and emerging artificial intelligence (AI) tools. Together, these approaches provide the scientific capacity to characterise hazard interactions, forecast extreme events, quantify uncertainty, and anticipate future risk trajectories under climate change.

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The second layer, operational intelligence, translates scientific understanding into flood-risk management practice. This layer incorporates exposure and vulnerability assessment, critical infrastructure analysis, early-warning systems, emergency response mechanisms, spatial planning, structural flood defences, Nature-based Solutions, and hybrid risk-reduction measures. Operational intelligence therefore extends beyond hazard prediction to address the practical management of risk, recognising that flood impacts are determined by the interaction between physical hazards and societal systems. Effective operational intelligence depends upon strong linkages between modelling outputs, emergency management structures, governance institutions, and local communities. Where such linkages are weak, responses remain fragmented, reactive, and poorly aligned with the realities of compound flood risk.

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The third layer, adaptive intelligence, focuses on long-term resilience building, institutional learning, and societal transformation. This layer incorporates adaptive governance, stakeholder participation, climate services, policy integration, vulnerability reduction, and Dynamic Adaptive Policy Pathways. Rather than treating adaptation as a fixed endpoint, adaptive intelligence recognises that compound flood risk evolves continuously under changing climatic, environmental, and socio-economic conditions. Consequently, resilience depends upon the ability of institutions and communities to learn, adjust, and reconfigure adaptation strategies over time. This perspective aligns closely with emerging concepts of Climate Resilient Development Pathways, which seek to integrate adaptation, sustainable development, environmental stewardship, and social justice within a single decision-making framework.

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A defining feature of the framework is the presence of iterative feedback loops linking the three intelligence layers. Predictive intelligence informs operational decisions through forecasting and risk assessment; operational intelligence generates observations, performance data, and experiential knowledge that refine predictive systems; and adaptive intelligence uses information from both layers to guide long-term planning and policy evolution. In turn, adaptation decisions influence future risk conditions, creating continuous feedback between environmental change, societal response, and flood management outcomes. Flood resilience therefore emerges not from any individual model, infrastructure asset, or adaptation measure, but from the capacity of the overall system to exchange information, coordinate actions, and learn across scales and sectors.

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The framework also explicitly recognises the importance of governance integration across the source-to-sea continuum. The findings of this review demonstrate that many barriers to compound flood resilience arise not from deficiencies in modelling capability, but from institutional fragmentation, sectoral silos, limited stakeholder engagement, and weak policy coherence.

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The framework therefore places governance at the centre of resilience-building, emphasising the need for coordinated decision-



making across catchment management, coastal planning, flood-risk management, climate adaptation, and environmental governance. In this regard, Cork Harbour provides a valuable living laboratory for understanding how scientific knowledge can be translated into operational practice and long-term adaptation within a complex coastal-estuarine system.

1210 Ultimately, the proposed Source-to-Sea Compound Flood Resilience Framework advances a shift from hazard-centred flood
management towards an integrated resilience paradigm. It argues that future flood resilience will depend not only on improved
models, stronger infrastructure, or innovative adaptation measures, but on the capacity of systems to connect predictive,
operational, and adaptive intelligence within a coherent, learning-oriented framework. By linking climatic drivers, flood
intelligence, risk management, governance, and adaptation pathways across the catchment–estuary–coast continuum, the
1215 framework provides a scientifically robust and transferable foundation for managing compound flood risk in coastal-estuarine
systems worldwide.

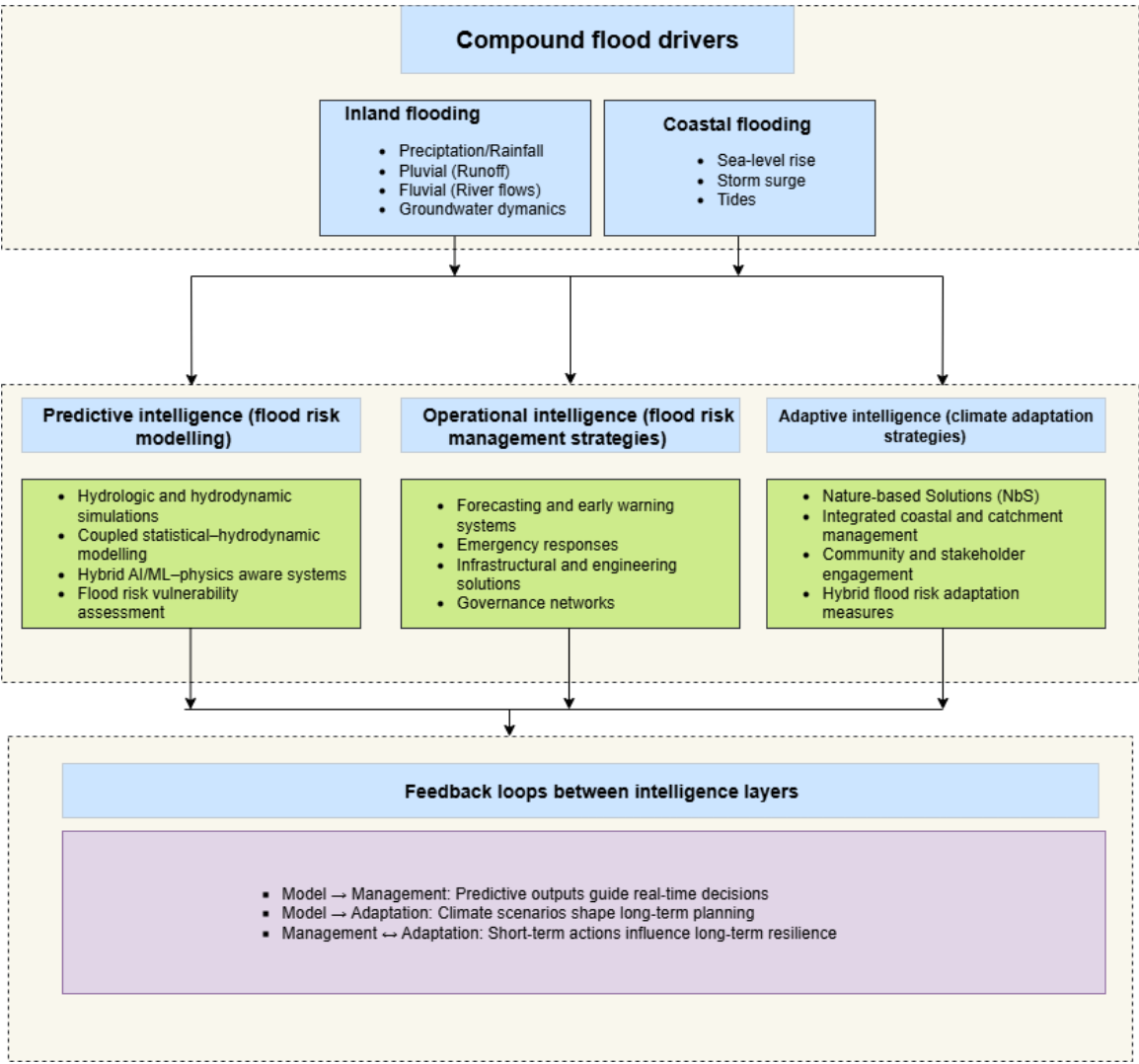


Figure 5: Integrated source-to-sea flood resilience intelligence framework.

4.7 Gaps and future research directions

No single location offers a perfect natural laboratory for compound flood research, yet sustained investment is essential if regions such as the CHC are to fully contribute to the global knowledge base on multi driver coastal hazards. The CHC system with its tightly coupled terrestrial, estuarine, and coastal processes requires long term research infrastructure, continuous monitoring, and iterative solution testing to establish transferable best practices. The insights generated through this review underscore the value of such systematic assessments and highlight the critical gaps that must be addressed to advance scientific understanding of land-sea-social dynamics and to develop viable, climate resilient long-term solutions.



Building on the synthesis of climatic drivers, modelling advances, governance analyses, and adaptation strategies, this paper identifies critical gaps that constrain both scientific understanding and climate-resilient decision-making in CHC and comparable coastal and estuarine systems globally. These gaps span modelling integration, observational infrastructure, biophysical processes, governance systems, equity, and long-term adaptive planning. Addressing them will require a research agenda that is integrated, interdisciplinary, data-rich, justice-centred, and explicitly designed for deep climate uncertainty. The following subsections synthesise the key research gaps and outline strategic future research directions for the next generation of compound-flood scholarship.

1. Development of fully integrated basin-to-harbour modelling frameworks: A dominant noticeable significant gap across the literature concerns the absence of fully coupled basin-to-harbour compound flood models. Current modelling approaches remain fragmented, with most studies unable to simultaneously simulate rainfall–runoff generation, groundwater responses, urban drainage, fluvial routing, tidal dynamics, storm-surge propagation, and wave impacts within a unified computational framework. This fragmentation undermines the representation of nonlinear, cross-scale dependencies that define compound events and limits predictive accuracy, particularly for the pluvial–groundwater–fluvial co-occurrence that characterises Cork City’s recent events. Future research must develop end-to-end, physics-consistent models that couple CHC hydrology, hydrodynamics, morphodynamics, and coastal processes, supported by multi-physics solvers and real-time data assimilation capable of accommodating climate-driven non-stationarity.

2. Advancing probabilistic and AI-enhanced compound flood prediction: There is a critical need for physics-informed AI, hybrid ML-hydrodynamic surrogates, and probabilistic deep-learning architectures that can quantify uncertainty and operate beyond the limits of historical training windows. Although multivariate statistical frameworks and ML models have improved compound-event understanding (Moradian et al., 2024; Olbert & Moradian, 2024), current flood forecasting and early-warning systems in Cork Harbour lack probabilistic, multi-hazard forecasting capable of jointly predicting pluvial, fluvial, tidal, and surge interactions. Advances in physics-informed deep neural networks (PIDNNs), hybrid ML–hydrodynamic architectures, and probabilistic deep learning offer opportunities to embed physical constraints, quantify uncertainty, and retain predictive skill under extreme and unprecedented conditions. A research priority is to develop AI-enhanced, multi-hazard early-warning systems that synthesise rainfall-runoff, tides, surges, soil moisture, groundwater, and drainage network conditions into a coherent decision-support system. Development of next-generation digital-twin CHC coupling hydrology, hydrodynamics, AI forecasting, and multi-scenario simulation should be prioritized.

Despite these advances, this review identified several gaps that warrant further investigation in the CHC region. Probabilistic modelling of joint likelihoods is still in its infancy, and calibration is constrained by limited observational data for extreme events. Advanced methods such as deep learning, graph neural networks, and physics-informed neural networks remain largely unexplored for the CHC region. Groundwater–surface water interactions and urban drainage systems, known to influence Cork Harbour’s flood dynamics, are rarely incorporated into flood models (Soboh et al., 2024, 2026).



3. Expanded monitoring infrastructure and real-time sensor networks: Robust compound-flood forecasting depends on dense, integrated observational systems. Establishment of a source-to-sea observation network, integrating Internet of things, sensors, tide gauges, nutrient probes, and remote-sensing for data assimilation should be prioritized. Cork Harbour requires an expanded network of tide gauges, surge sensors, hydrometric stations, soil-moisture probes, radar rainfall systems, and IoT-enabled drainage sensors, supported by continuous data assimilation and open-access data platforms. Such systems would reduce uncertainty, improve model calibration, and strengthen early-warning and decision-support capacities.

4. Integration of NbS: In Cork Harbour NbS show clear benefits in upstream catchments and early hybridisation is evident in LLFRS and the Marina Park 2 project, but further steps are required. Their performance under multi-driver compound climatic pressures remains poorly understood. Key future priorities could include: (a) systematic valuation and cost–benefit analysis of green–grey systems; (b) alignment of upstream NbS (e.g., detention basins, woodland swales) with downstream urban defences; (c) integrated management across land–sea interfaces; and (d) embedding NbS performance metrics in FRM policy. Future research must also undertake long-term ecological, hydrological, and biogeochemical monitoring, accompanied by process-based modelling, to determine how NbS interact with fluvial peaks, surges, tides, and groundwater dynamics. Equally important is evaluating NbS through cost-benefit analysis frameworks that capture carbon sequestration, biodiversity gains, recreation, and urban cooling.

5. High-resolution social vulnerability mapping and climate justice: Despite growing recognition of vulnerability and equity concerns, Cork lacks granular, spatially explicit assessments of socio-economic sensitivity, adaptive capacity, and exposure (Jeffers, 2013; McCullagh et al., 2025). Research should integrate hazard models with multi-criteria social vulnerability indicators (age, disability, tenure, income, mobility, language, health) to support equitable, just flood resilience planning and resource allocation (McCullagh et al., 2025). Such datasets are essential for understanding who is most impacted by compound flood events and why.

6. Governance and participatory modelling: Persistent governance fragmentation, technocratic risk framings, and contested flood-defence decisions underscore the need for participatory, experimental governance approaches. Research should test co-production methodologies, participatory scenario workshops, risk visualisation, and citizen-science flood monitoring, building on insights from the Lower Lee Scheme dispute (Jeffers, 2017; Jeffers, 2020). These tools can enhance trust, broaden constituencies, and enable adaptive governance that reflects community values, risk perceptions, and place attachments.

7. Dynamic adaptation pathways for long-term resilience: Given deep uncertainty in climate trajectories, demographic change, and tidal regimes, Cork Harbour requires Dynamic Adaptation Pathways (Langendijk et al., 2025) to sequence



1295 structural, ecological, and governance measures over long time horizons. Future research should define trigger points, decision
thresholds, and sequencing strategies for hybrid interventions, ensuring that adaptation investments remain flexible,
“no-regrets,” and compatible with evolving compound-flood regimes. Integrating DAP with probabilistic modelling and ICZM
frameworks would provide Cork Harbour with a future-proof, flexible planning and decision-making architecture.
Collectively, these research directions call for a new phase of compound-flood scholarship one that is interdisciplinary, data-
1300 rich, AI-enhanced, NbS integrated, social-ecological resilient, equity-attuned, and oriented toward adaptive, participatory
governance. These priorities can transform Cork Harbour into a living laboratory for compound-flood resilience, providing
transferable insights for coastal–estuarine systems globally.

5. Conclusions

1305 This systematic review provides the first comprehensive synthesis of CoMF in CHC, yet its relevance extends far beyond
Ireland, offering internationally transferable insights into how multi-driver flood hazards unfold, how they can be modelled
with scientific rigour, and how socio-institutional systems shape resilience. By consolidating three decades of research on
climatic drivers, multivariate hydrodynamics, governance, and adaptation, this review delivers a coherent analytical template
for understanding river–estuary–coastal interactions and demonstrates how non-linear feedback between extreme precipitation,
1310 fluvial discharge, storm surge, tidal modulation, sea-level rise, and antecedent hydrology generate complex CoMF events.
Crucially, the synthesis shows that CHC is undergoing a mechanistic transition: while fluvial processes currently dominate,
projected SLR and surge intensification could increase coastal inundation by up to 400%, surpassing fluvial contributions and
fundamentally restructuring hazard hierarchies. This pattern mirrors trajectories anticipated across estuarine cities in Europe,
North America, and Asia, making CHC a globally relevant model system for diagnosing, modelling, and adapting to compound
1315 flood risk under climate change.

Internationally, the findings highlight three overarching lessons. First, advances in flood modelling particularly high-resolution
nested hydrodynamic frameworks (i.e. MSN_Flood), multivariate statistical–hydrodynamic frameworks, and hybrid
machine-learning surrogates have improved simulation fidelity and mechanistic understanding. Yet several limitations gaps
remain, including insufficient probabilistic treatment of joint extremes, real-time continuous data, integration of socio-
1320 economic vulnerability metrics, probabilistic modelling, uncertainty quantification, AI-enhanced real-time forecasting, and the
integration of urban drainage and groundwater processes. compound flood risk cannot be understood or managed through
single-driver frameworks: it requires multivariate modelling, integrated monitoring, and physics-informed AI to capture
dependencies and non-stationarity. Addressing these gaps is essential for robust real time forecasting, early-warning systems,
and long-term adaptation planning.

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Second, flood risk management in the CHC region remains dominated by structural engineering measures such as the LLFRS.
While these defences provide essential protection, they face social contestation, escalating climate exceedances, and inherent



inflexibility under deep uncertainty. Governance fragmentation, technocratic decision-making, and limited public engagement—as seen in the LLFRS conflict—are not local anomalies but structural barriers observed globally; addressing them demands participatory, equitable, and adaptive governance.

Third, there is increasing emphasis on non-structural and ecosystem-based measures such as NbS, ICZM, forecasting and early-warning systems, stakeholder engagement, social vulnerability, equity and justice considerations, and adaptive governance, reflecting a gradual but incomplete transition toward a more holistic FRM paradigm. Hybrid green–grey strategies, combining structural flood defences with NbS, provide the most robust pathway for long-term resilience, aligning with global adaptation frameworks.

Looking forward, this review identifies six priority research directions: (i) mainstreaming probabilistic and machine-learning approaches for compound hazard prediction; (ii) developing integrated modelling frameworks coupling climatic, hydrodynamic, and socio-ecological systems; (iii) expanding continuous monitoring infrastructure; (iv) deploying sensor networks for real-time data acquisition; (v) operationalising AI-driven forecasting platforms; and (vi) embedding adaptive governance to enable hybrid portfolios of structural, non-structural, and nature-based measures. Hybrid green–grey approaches offer the greatest potential for robust, flexible adaptation under uncertainty. These priorities are not only locally actionable but globally relevant, offering a blueprint for estuarine cities confronting similar compound-flood dynamics under accelerating climate change. Overall, the findings call for a decisive move toward hybrid, participatory, adaptive governance, compound-sensitive, and climate resilient adaptation grounded in Climate Resilient Development Pathways. Only through such integrated, flexible, and socially legitimate strategies can Cork Harbour build resilience to accelerating compound flood risks and safeguard its communities, ecosystems, and infrastructure in a changing climate. By synthesising three decades of flood research in Cork Harbour, this review contributes an internationally relevant blueprint for climate-resilient coastal adaptation. The insights presented here are directly applicable to estuarine catchments globally, offering conceptual, methodological, and governance innovations urgently needed to confront accelerating compound-flood risks under climate change.

Author contributions

Ashenafi Yohannes Battamo: Conceptualization, methodology, literature search, data curation, formal analysis, synthesis of results, framework development, visualization, writing of the original draft, and manuscript revision.

Rory Scarrott: Conceptualization, supervision, methodological guidance, critical review and editing of the manuscript, interpretation of results, and validation of the study.

Jeremy Gault: Resources and securing fund, supervision, critical review and editing, scientific input on flood modelling, flood risk management, and climate adaptation, and overall project oversight.

Anne Marie O'Hagan: Resources and securing fund, supervision, critical review and editing, and overall project oversight.



All authors contributed to the interpretation of the findings, reviewed the manuscript, and approved the final version for publication.

Competing interests

The authors declare that they have no competing interests.

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