Review Article:
A Comprehensive Review of Compound Flooding Literature with a Focus on Coastal and Estuarine Regions

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Abstract

Compound flooding, where the combination or successive occurrence of two or more flood drivers leads to a greater impact, can exacerbate the adverse consequences of flooding, particularly in coastal/estuarine regions. This paper reviews the practices and trends in coastal/estuarine compound flood research and synthesizes regional to global findings. Systematic review is employed to construct a literature database of 279 studies relevant to compound flooding in a coastal/estuarine context. This review explores the types of compound flood events, their mechanistic processes, and synthesizes terminology throughout the literature. Considered in the review are six flood drivers (fluvial, pluvial, coastal, groundwater, damming/dam failure, and tsunami) and five precursor events and environmental conditions (soil moisture, snow, temp/heat, fire, and drought). Furthermore, this review summarizes research methodology and study application trends, as well as considers the influences of climate change and urban environments. Finally, this review highlights knowledge gaps in compound flood research and discusses the implications on future practices. Our five recommendations for compound flood research are: 1) adopt consistent terminology and approaches; 2) expand the geographic coverage of research; 3) pursue more inter-comparison projects; 4) develop modelling frameworks that better couple dynamic Earth systems; and 5) design urban and coastal infrastructure with compounding in mind.

Short Summary

Compound flooding, involving the combination or successive occurrence of two or more flood drivers, can amplify flood impacts in coastal/estuarine regions. This paper reviews the practices, trends, methodologies, applications, and findings of coastal compound flooding literature at regional to global scales. We explore the types of compound flood events, their mechanistic processes, and the range of terminology. Lastly, this review highlights knowledge gaps and implications for future practices.

Key Words: Compound Flood, Compound Event, Flood Driver, Coastal Flood, Coastal Hazard

1) Introduction

Flooding is the costliest and most common hazard worldwide (Bevere and Remondi, 2022; Mishra et al., 2022; Rentschler et al., 2022), and can lead to a wide range of environmental, economic, and social repercussions. Over 1.8 billion people, almost a quarter (23%) of the world's population, are exposed to 1-in-100 year flooding (Rentschler et al., 2022). The vast majority (89%) of these people live in low- and middle-income countries, and socially vulnerable communities are disproportionately at risk (Rentschler et al., 2022). Since 1980, global floods have caused over 250,000 fatalities and $1 trillion USD in losses (Re, 2017; Em-Dat, 2022). In 2021 alone there were more than 50 severe flood disasters recorded worldwide, causing economic losses totaling $82 billion (2022 USD) (Bevere and Remondi, 2022).

A large proportion of deaths and the economic losses associated with flooding have historically occurred in densely populated coastal/estuarine regions. Today, near-coastal zones and low-elevation coastal zones, subject to flooding from a range of drivers, are respectively home to 2.15 billion and ~900 million people globally (Reimann et al., 2023). In the past decade, floods associated with strong onshore wind and pressure fields (e.g., 2013/2014 UK Winter Floods, 2017 Atlantic Hurricane Season, 2019 Atlantic Hurricane Dorian, 2019 East Africa Tropical Cyclone Idai, 2019 Pacific Typhoon Season, and 2022 Eastern Australia Floods) have showcased the ever-present threat of extreme flood impacts in coastal settings. Even in regions where coastal defence standards are among the highest in the world (e.g., Europe, Japan, Netherlands), potential defence failure during events that exceed the standard of protection (e.g., major overtopping or a breach) still poses considerable risk to populations and development in coastal floodplains. Moreover, flooding is a rapidly growing threat to most coastal regions and their communities due to: (i) sea-level rise, changes in storminess, and increasingly variable rainfall patterns driven by climate change (Church et al., 2001; Wood et al., 2023); (ii) population growth, urbanization, and continued development in floodplains (Hallegatte et al., 2013); and (iii) the continued decline in the extent of shorelines and habitats which act as natural buffers to flooding (Woodruff et al., 2013; Oppenheimer et al., 2019).

Average global flood losses in large coastal cities are estimated to increase approximately tenfold by 2050 due to socio-economic change alone, reaching up to US$1 trillion or more per year when considering sea-level rise and land subsidence (Hallegatte et al., 2013). There is clear importance in advancing our understanding of flooding in coastal/estuarine regions.

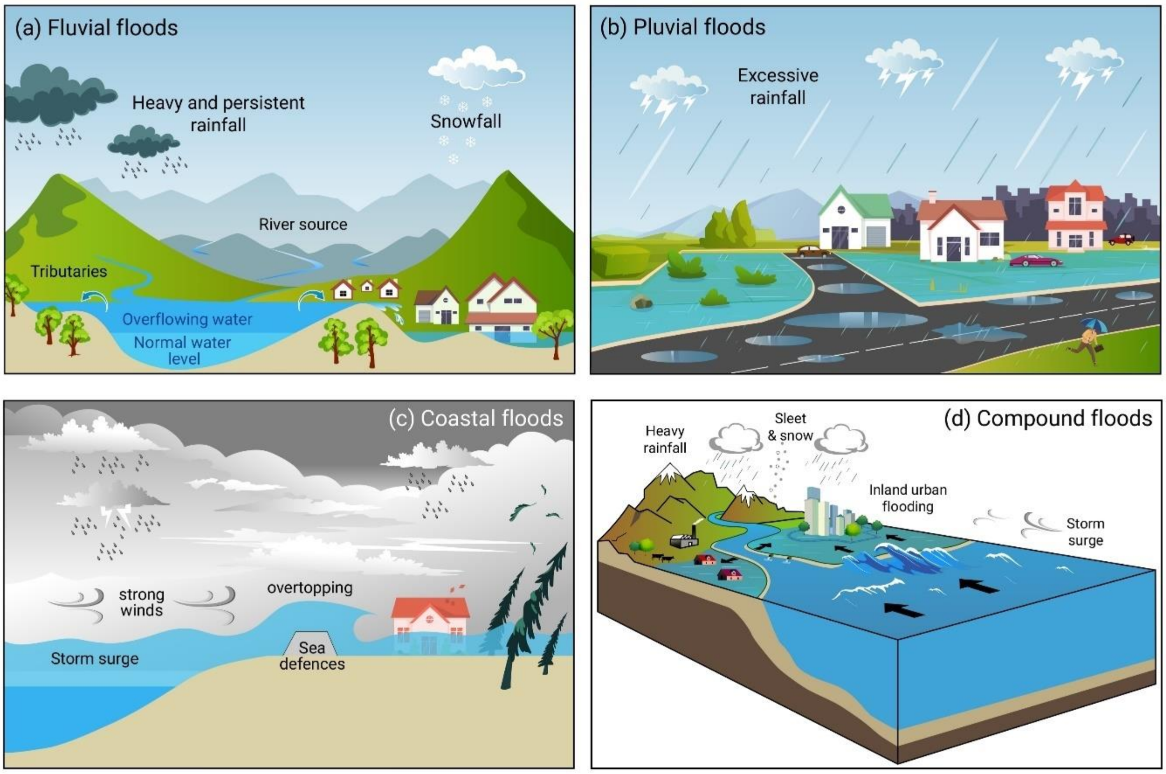


Figure 1. Schematic diagram of flood drivers showing (a) fluvial (river discharge), (b) pluvial (rainfall-runoff), and (c) coastal (surge, tide, waves, and total sea level) components, as well as their (d) compound flood interactions.

This review focuses on compound flooding that takes place in coastal (ocean/lake) and estuarine regions, which primarily arises from three main drivers: (1a) river discharge (**fluvial**); (1b) precipitation surface runoff (**pluvial**); and (1c) coastal processes including storm surge, astronomical tides, wave action, and relative sea level rise (SLR) (**coastal**) as shown in Figure 1. Traditionally, most existing flood risk assessments consider these main drivers of flooding separately; and many oversimplify or ignore key interactions altogether. However, in many coastal/estuarine regions, floods are often caused by more than one driver as the processes are naturally correlated. For example, intense tropical/extratropical cyclones (TCs/ETCs) can generate heavy precipitation that enhances river discharges, while at the same time strong winds and low pressures cause large storm surges and waves. When fluvial, pluvial, and/or coastal drivers occur at the same time, or within a few hours or days, the adverse effects of flooding can be measurably exacerbated (Gori et al., 2020a; Khalil et al., 2022). The synergy of multiple hazard drivers can result in disproportionately extreme events, even if individual flood drivers are not extreme themselves. This is often referred to as 'compound events' (Hewitt and Burton, 1971; Adhikari et al., 2010; Seneviratne et al., 2012; Leonard et al., 2014; Zscheischler et al., 2020). It is only in the last decade that we are beginning to recognize the necessity of compound event-based approaches to flood risk assessment, as traditional univariate methods of analysis fail to capture the non-linear impacts of multiple flood drivers (Kappes et al., 2010; Leonard et al., 2014; Eshrati et al., 2015; Klerk et al., 2015; Ridder et al., 2018; Zscheischler et al., 2018; Hao and Singh, 2020; Ridder et al., 2020; Manoj J et al., 2022).

In recent decades our knowledge of individual flood drivers has improved tremendously, as a result of better in-situ and remote sensed datasets, and advances in statistical and numerical modelling techniques. However, our understanding of compound flood events is still limited, from the synergetic processes to the spatiotemporal trends and scales of interacting drivers. Compound event-based research is relatively new (Wu et al., 2020; Bevacqua et al., 2021), having only gained notable attention in 2012 when it was formally defined in the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Climate Extremes (SREX) (Seneviratne et al., 2012), and as a key guiding principle of the 2015 UN Sendai Framework on Disaster Risk Reduction (UNDRR, 2015). Additionally, there has been growing public awareness of extreme compound flooding following a decade of increasingly frequent extreme weather events, where catastrophic disasters arose from multiple interacting flood drivers. For example, in 2017 Hurricane Harvey resulted in record-breaking rainfall, river discharge, and runoff, which when combined with long-lasting storm surge resulted in catastrophic flooding in Houston, Texas (Valle-Levinson et al., 2020; Huang et al., 2021; Gutenson et al., 2022). This was the second costliest ($152.5B) natural hazard in US history (NCEI, 2023). As a result of this event, it has been recognised that by failing to consider compound flooding, the risk to Houston and elsewhere had been, and currently remains, greatly underestimated.

Compound flood research at local, regional, and recently global scales has experienced growing recognition and substantial advancements over the past decade, with rapid increases in the number of academic publications (particularly since 2020). However, to date, there have only been a handful of published reviews that have synthesized the current understanding of compound flooding. Moreover, the reviews that do exist have only focused on specific elements of the broader compound flood subject. Bensi et al. (2020) reviewed the drivers and mechanisms of compound flooding, the methods of joint distribution analysis regarding probability hazard assessment, and the key findings of various bivariate coastal-fluvial and coastal-pluvial flood studies. Recently, Guan et al. (2023) completed a brief review of 13 compound pluvial-fluvial flood papers, synthesizing case studies, approaches, and knowledge gaps; in addition to highlighting the value of including damage models in risk management. To the best of our knowledge, three publications have reviewed compound flood modelling approaches in coastal regions (Santiago-Collazo et al., 2019; Xu et al., 2022; Jafarzadegan et al., 2023) . Santiago-Collazo et al. (2019) summarized practices of numerical compound flood modelling methodologies including different frameworks for linking (or coupling) multiple hydrologic, hydrodynamic, and ocean circulation models. Xu et al. (2022) examined the advancements, benefits, limitations, and uncertainties of varying numerical and statistical (joint probability and dependence) models and frameworks for compound flood inundation. Lastly, Jafarzadegan et al. (2023) provided a general review of advancements in both univariate riverine and coastal modelling, briefly touching on a hybrid compound modelling approach using linked statistical-hydrodynamic models and physics-informed machine learning (ML). More broadly, two additional papers by Hao et al. (2018) and Zhang et al. (2021a) reviewed the advancing work on compound flood extremes in the realm of hydrometeorology, evaluating the physical drivers and underlying mechanisms (Hao et al., 2018) plus analytical and modelling research methods (Zhang et al., 2021a). Hao et al. (2018) outlined the characteristics and key statistical tools for assessing compound flood and other compound hydroclimatic extremes (drought, heatwave, coldwave, extreme rainfall). Zhang et al. (2021a) discussed these same statistical approaches when reviewing drivers, mechanisms, and means of quantifying risk for compound flooding and four other compound extremes (drought, hot-wet, cold-wet, cold-dry). In addition, they reflected on methods of numerical modelling and collated findings on pluvial-surge, fluvial-surge, sea level-tide, and fluvial-tide compound flood studies. Regarding compound events and driver dependence, Hao and Singh (2020) and Zscheischler and Seneviratne (2017) reviewed standard methods of measuring dependence (using copulas) as well as approaches for quantifying the likelihood of compound floods. Abbaszadeh et al. (2022) reviewed the sources and challenges of uncertainty in flood modelling and forecasting and offered guidance on reducing uncertainty in the context of compound floods. In addition to these aforementioned papers that reviewed specific aspects of compound flooding, there are several articles (e.g., Leonard et al. (2014); Aghakouchak et al. (2020); Ridder et al. (2020); Zscheischler et al. (2020); Bevacqua et al. (2021); Simmonds et al. (2022); Van Den Hurk et al. (2023)) that have reviewed broader compound event research involving a range of hazards beyond just flooding. These papers have discussed compound flooding and provide a diversity of detailed case examples, but largely focus on the frameworks, typologies, theories, and perspectives of compound event-based research and disaster risk reduction as a whole (Leonard et al., 2014; Aghakouchak et al., 2020; Ridder et al., 2020; Zscheischler et al., 2020; Bevacqua et al., 2021; Simmonds et al., 2022). Overall, these previous reviews have provided an excellent synthesis of specific aspects of compound flooding, however, they have each only focused on a narrow area within the much broader compound flooding discipline. To date, a detailed state-of-the-art review of the entire body of compound flood literature has yet to be done.

Therefore, the overall aim of this paper is to carry out a comprehensive systematic review and synthesis of compound flood literature, with a focus on coastal/estuarine regions where compound flooding is most prevalent. We stress that this is not a review of coastal flooding, but rather compound flooding occurring in coastal (ocean/lake) and estuarine settings.

To address this aim we have six objectives around which the paper is structured:

1. To survey the range of compound event definitions and terminologies, and examine how they pertain to the scope of compound flooding (Section 2);
2. To briefly discuss the key physical processes contributing to flood events from individual drivers (Section 3);
3. To develop an extensive literature database on compound flood research in coastal/estuarine regions (Section 4);
4. To identify trends in the characteristics of compound flood research (Section 5);
5. To synthesize the key findings (dependence hotspots and driver dominance), considerations (coastal urban infrastructure and climate change), and standard practices (application cases and analytical methods) of compound flood research (Section 6); and
6. To reflect on the knowledge gaps in multivariate flood hazard research and suggest potential directions for research going forward (Section 7).

Finally, overall conclusions are given (Section 8). Compound flood research is a rapidly developing field of science. As well as providing a comprehensive review, identifying knowledge gaps, and suggesting potential areas for future research, one of our secondary goals of this paper is to provide an initial starting point to better inform researchers and decision-makers new to the emerging field.

2) Definitions and Types of Compound Events & Multi-hazard Events

Our first objective is to survey the range of compound event terminologies observed in literature, and to establish the scope of compound flooding considered in this review. First, we do this broadly, reflecting on the definitions of compound events across different types of hazards (and risks) that have been defined in the literature, and then we examine how the various definitions pertain specifically to compound flood types and accompanying drivers. After this, we seek to champion a unifying definition framework (i.e., encompasses a diversity of perspectives and use-cases around compound events) for this review.

Throughout natural hazard literature, terminology around 'compound event, 'compound hazard', and 'multi-hazard' are highly inconsistent. In the past, these terms have sometimes been applied interchangeably. Some refer to compound hazards as a type of multi-hazard event within the larger umbrella of the multi-hazard framework. We believe each of these terms are distinct from one another, and thus for the purposes of this review we use the phrase 'compound event'. Examples of different compound event (and related) terminologies are listed in Table 1 (general disaster and hazard definitions are also provided for context). Several terms have been used to describe similar concepts that all broadly involve the consideration of multiple hazards, drivers, mechanisms, variables, and extremes in a multivariate and non-linear assessment of risk (i.e., hazard exposure x vulnerability x capacity) and impact as defined by the IPCC (IPCC, 2012, 2014).

Use of the term 'compound event' (and similar phrases) has been observed in older academic publications (Hewitt and Burton, 1971), however it was only formally defined in an official context in the 2012 IPCC SREX (Seneviratne et al., 2012). As of present, the most widely accepted definitions of compound events are those from the IPCC SREX (Seneviratne et al., 2012), Leonard et al. (2014), and Zscheischler et al. (2020), which we briefly discuss below.

The IPCC SREX (Seneviratne et al., 2012) defines compound events as a combination of multiple divers or hazards with adverse environmental or social risk/impact. A more detailed explanation is as follows:

> *"(1) two or more extreme events occurring simultaneously or successively, (2) combinations of extreme events with underlying conditions that amplify the impact of the events, or (3) combinations of events that are not themselves extremes but lead to an extreme event or impact when combined. The contributing events can be of similar (clustered multiple events) or different type(s)"*

According to this definition, compound flooding could, for instance, describe the occurrence of a moderate rainfall event that causes surface runoff and discharges at the coast, in addition to elevated coastal water levels from storm surge and wave action (whether simultaneous or a few days later). None, one, or both of the two events may be considered extreme according to threshold or probability-based approaches, but together they lead to extreme coastal water levels. This definition also emphasizes the potential for compounding from the temporal clustering of the same (or different) types of events (e.g., storm clustering involving quick succession of storm events and associated coastal hazards (Jenkins et al., 2023)).

Leonard et al. (2014) argue that the IPCC SREX (Seneviratne et al., 2012) definition is unable to capture extreme event edge cases (i.e., unexpected or outlier situations) and is not founded on the physical systems at play. They instead propose a definition that focuses on the variable interactions and event impact, as follows:

> *"Our definition emphasizes three characteristics: (1) the extremeness of the impact rather than the climate or weather event; (2) the multivariate nature of the event; and (3) statistical dependence between variables or events that cause the impact."*

Thus, according to this definition, the classification of compound flood events necessitates an extreme impact. In the context of flooding, the IPCC SREX may recognize, for example, the simultaneous overtopping of riverine channels and surfacing of groundwater as compounding. However, unless the impact is extreme, it would not pass as a compound flood according to Leonard et al. (2014). This interpretation also requires definitive dependence between the extremes in question. Therefore, a fluke spatiotemporal overlap of extreme rainfall due to an atmospheric river in a region with elevated river levels from recent snowmelt would not be considered a compound flood as the two events are fully independent. In contrast, an intense multivariate storm event involving dependent extreme storm surge and intense rainfall is deemed a compound event.

More recently, Zscheischler et al. (2018) proposed a broader definition that is specific to compound weather/climate events, as follows:

> “*The combination of multiple drivers and/or hazards that contributes to societal or environmental risk*.”

Under this definition, the extremeness of individual drivers and/or hazards is not considered, however their combination must still exhibit some extent of impact to contribute to overall risk. Furthermore, compound events are strictly limited to the combination of natural (weather/climate) drivers and hazards. Thus, anthropogenic hazards (e.g., dam failure and deforestation) are not included within their scope of compound events. To date, the definition proposed by Zscheischler et al. (2018) offers strong potential for a unified discussion of compound climate events across scientific disciplines. In the past few years, numerous compound flood studies have accordingly adopted their definition framework (Hao and Singh, 2020; Ridder et al., 2020; Bevacqua et al., 2021; Zhang et al., 2021a; Xu et al., 2022).

Finally, for the scope of this review, we adopt the IPCC definitions of ‘hazard’ and ‘compound event’ (IPCC, 2012; Seneviratne et al., 2012), and thus consider compound events as a combination of two or more co-occurring or consecutive drivers (natural or anthropogenic), that together have a greater impact than either of the individual events. Neither the individual driver nor their combinations must explicitly be considered extreme. Potential driver interaction types within this compound event framework include the temporal and/or spatially overlapping combination of multiple hazards (often from shared modulators, e.g., storm event prompts simultaneously rainfall and storm surge), the direct triggering or cascading of one hazard by another (e.g., heavy rainfall on top of existing bankfull river discharge), and the random or by-chance spatial/temporal overlapping of independent hazards (e.g., atmospheric river rainfall during peak spring snowmelt).

Term Category	Reference	Term	Definition
General	UNDRR (2016)	Disaster	A serious disruption of the functioning of a community or a society at any scale due to **hazardous events interacting with conditions of exposure, vulnerability, and capacity**, leading to one or more of the following: human, material, economic, and environmental **losses and impacts**.
General	IPCC (2012)	Disaster	Severe alterations in the normal functioning of a community or a society due to **hazardous physical events interacting with vulnerable social conditions**, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery.
General	UNDRR (2016)	Hazard	**A process, phenomenon, or human activity** that may cause loss of life, injury or other health impacts, property damage, social and economic disruption, or environmental degradation.
General	IPCC (2012)	Hazard	The potential occurrence of a **natural or human-induced physical event** that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources.
General	IPCC (2012)	Disaster Risk	The likelihood over a specified time period of severe alterations in the normal functioning of a community or a society due to **hazardous physical events interacting with vulnerable social conditions**, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery.
General	UNDRR (2016)	Disaster Risk	The potential loss of life, injury, or destroyed or damaged assets that could occur to a system, society, or a community in a specific period of time, determined probabilistically as a function of **hazard, exposure, vulnerability, and capacity**.
General	IPCC (2012)	Impacts	The **effects** on natural and human systems of **physical events, of disasters, and of climate change**.
General	UNDRR (2016)	Disaster Impact	The **total effect**, including negative effects (e.g., economic losses) and positive effects (e.g., economic gains), of a **hazardous event or a disaster**. The term includes economic, human, and environmental impacts, and may include death, injuries, disease, and other negative effects on human physical, mental, and social well-being.
General	Herring (2020)	Extreme Event	A time and place in which **weather, climate, or environmental conditions**—such as temperature, precipitation, drought, or flooding— statistically **rank above a threshold value** near the upper or lower ends of the range of historical measurements. Though the threshold is subjective, some scientists define extreme events as those that occur in the highest or lowest 5% or 10% of historical measurements. Other times they describe events by how far they are from the mean, or by their recurrence interval or probability.
General	Sarewitz and Pielke (2001)	Extreme Event	An occurrence that, with respect to some class of occurrences, is either **notable, rare, unique, profound, or otherwise significant in terms of its impacts, effects or outcomes**. An extreme event is not simply 'something big and rare and different'. 'Eventness' demands some type of temporal and spatial boundaries, while 'extremeness' reflects an event's potential to cause change.
General	IPCC (2014)	Extreme Weather Event	An **extreme weather event** is an event that is **rare at a particular place and time of year**. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. The characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season).
Multi-	UNDRR (2016)	Multi-hazard	1) The selection of **multiple major hazards** that the country faces, and 2) The specific contexts where **hazardous events may occur simultaneously, cascadingly, or cumulatively** over time, and taking into account the potential interrelated effects

Multi-	Zschau (2017)	Multi-hazard	**More than one hazard** where hazard interactions are considered
Multi-	Komendantova et al. (2014)	Multi-hazard	The analysis of different relevant **hazards, triggering, and cascade effects** threatening the same exposed elements **with or without temporal concurrence.**
Multi-	Tilloy et al. (2019)	Multi-hazard	**More than one natural hazard with interrelationships** between the hazards that impact the **same location and time period**.
Multi-	Gill and Malamud (2014)	Multihazards	**All possible and relevant hazards, and their interactions**, in a given **spatial region and/or temporal period**
Multi-	Hewitt and Burton (1971)	Multiple Hazards	**Elements** of quite different kinds **coinciding accidentally, or more often, following one another** with damaging force, for instance floods in the midst of a drought, or hurricanes followed by landslides and floods.
Multi-	Zschau (2017)	Multi-hazard Risk	Risk in a **multihazard** framework where **no hazard interactions are considered** on the vulnerability level
Multi-	Eshrati et al. (2015)	Multi-hazards Risk	**The consideration of multiple** (if possible all relevant) **hazards** posing risk to a certain area under observation.
Multi-	Kappes et al. (2010)	Multi-hazard Risk	The **totality of relevant hazards in a defined area**. Hazards are, as natural processes, part of the same overall system, influence each other and interact. Thus, **multi-hazard risk** contains emergent properties: It is not just the sum of single-hazard risks since their relations would not be considered and this would lead to unexpected effects.
Multi-	Kappes et al. (2012)	Multi-hazard Risk	A first definition of the term '**multi-hazard**' in a risk reduction context could read as follows: the **totality of relevant hazards in a defined area** (Kappes 2011). However, whether a hazardous process is relevant has to be defined according to the specific setting of the respective area and the objective of the study. Additionally, not all studies on multiple hazards share the aim of involving '**all relevant processes of a defined area**' but can rather be described as **'more-than-one-hazard**' approaches. In summary, two approaches to multi-hazard can be distinguished: 1) **primarily spatially oriented** and aims at including all relevant hazards, and 2) **primarily thematically defined**.
Multi-	Eshrati et al. (2015)	Multi-hazards Interaction Types	Hazards relationship refers to many different types of influence of hazards to each other. 1) **Triggering** of a hazard by another 2) **Simultaneous impact** of several hazards due to the same triggering event 3) **Disposition alteration** of a hazard after another hazard occurrence 4) **Multiple effects** of a hazard phenomenon
Multi-	Tilloy et al. (2019)	Multi-hazards Interaction Types	1) **Independence** where spatial and temporal overlapping of the impact of two hazards without any dependence or triggering relationship 2) **Triggering/Cascading** where a primary hazard that triggers and a secondary hazard 3) **Change Conditions**: one hazard altering the disposition of a second hazard by changing environmental conditions 4) **Compound hazard (association)** where different hazards are the result of the same "primary event", or large-scale processes which are not necessarily a hazard 5) **Mutual exclusion (negative dependence)** where two hazards can also exhibit negative dependence or be mutually exclusive
Multi-	Kappes et al. (2010)	Multi-hazard Interaction Types	1) **Disposition Altering** where modification of environmental characteristics, whether long-term basic disposition (e.g., relief, climate, vegetation cover) or

			faster variable disposition (e.g. daily to seasonal weather, water balance, vegetation period) causes the exceedance of a threshold and resulting hazard 2) **Triggering/Cascading** where one hazard is directly triggered or provoked by another hazard, or a chain of two or more hazards are induced as a result of a shared external event
Multi-	Gill and Malamud (2014)	Multihazard Interaction Types	Multiple hazard interaction types are divided into four categories: 1) **Coincidence relationship** involving the spatial and temporal coincidence of natural hazards. 2) **Triggering relationship** where a hazard is triggered. (e.g., lightning triggering a wildfire, groundwater abstraction triggering regional subsidence, a flood triggering a landslide which then triggers a further flood) 3) **Increased probability relationship** where the probability of a hazard in increased. (e.g., a wildfire increasing the probability of landslides, regional subsidence increasing the probability of flooding) 4) **Decreased probability relationship** where the probability of a hazard is decreased. (e.g., urbanisation catalysing storm-triggered flooding, storms impeding urban fire-triggered structural collapse)
Multi-	Zschau (2017)	Multi-risk	Risk in a **multi-hazard** framework where **hazard interactions are considered** on the vulnerability level.
Multi-	Komendantova et al. (2014)	Multi-risk	A comprehensive risk defined from **interactions between all possible hazards and vulnerabilities**.
Compound / Other	IPCC SREX (Seneviratne et al. (2012)) IPCC (2012)	Compound Event	In climate science, compound events can be: 1) **Two or more extreme events occurring simultaneously or successively**, 2) **Combinations of extreme events** with underlying **conditions that amplify the impacts** of the events, or 3) **Combinations of events** that are not themselves extreme but **lead to an extreme event or impact** when combined. The contributing events can be of similar (clustered multiple events) or different types. Examples of compound events resulting from events of different types are varied – for instance, high sea level coinciding with tropical cyclone landfall, or cold and dry conditions (e.g., the Mongolian Dzud), or the impact of hot events and droughts and wildfire, or a combined risk of flooding from sea level surges and precipitation-induced high river discharge (Svensson and Jones, 2002; Van den Brink et al., 2005). Compound events can even result from 'contrasting extremes', for example, the projected occurrence of both droughts and heavy precipitation events in future climates in some regions.
Compound / Other	Hewitt and Burton (1971)	Compound Event	**Several elements acting together above their respective damage threshold,** for instance wind, hail, and lightning damage in a severe storm. Many of the most severe meteorological hazards are **compound**, or become disastrous through involvement in a **multiple hazard situation.**
Compound / Other	Leonard et al. (2014)	Compound Event	Emphasizes three key characteristics of a **compound event**: (1) the **extremeness of the impact** rather than variables or events it depends on; (2) the requirement of **multiple variables or events** on which the impact depends; and (3) the role of **statistical dependence**. Consider a coastal flood where the flood level depends on a rainfall event and an elevated ocean level. The coastal flood is a compound event because (1) the impact metric, a flood level, is considered to be extreme; (2) the impact depends on multiple variables, the rainfall and ocean boundary; and (3) the ocean level can have a statistical dependence with rainfall due to influences such as storm surge, wind setup, or seasonality.
Compound / Other	Zscheischler et al. (2018)	Compound Event	**Compound weather and climate events** are the **combination of multiple drivers and/or hazards** that contribute to societal or environmental risk. Drivers include processes, variables, and phenomena in the climate and weather domain that may span over multiple spatial and temporal scales. Hazards are usually the immediate physical precursors to negative impacts (such as floods, heatwaves, and wildfire), but can occasionally have positive outcomes (for example, greening in the Alps during the 2003 heatwave in Europe).

Compound / Other	Zscheischler et al. (2020)	Compound Event Interaction Types	**Compound weather and climate events** have been organized into four type classes: 1) **Preconditioned**: where a hazard causes or leads to an amplified impact because of a precondition 2) **Multivariate**: co-occurrence of multiple climate drivers and/or hazards in the same geographical region causing an impact 3) **Temporally Compounding (sequential)**: succession of hazards that affect a given geographical region, leading to, or amplifying, an impact compared with a single hazard 4) **Spatially Compounding**: events where spatially co-occurring hazards cause an impact
Compound / Other	Raymond et al. (2020)	Connected Extreme Event	The concept of **connected extreme weather and climate events** further recognizes that **compound event impacts** are often substantially and nonlinearly influenced by non-physical factors such as exposure and vulnerability, cutting across sectors and scales (from personal to society wide). These 'societal mechanisms' can tie together the impacts **of two or more climate extremes**. It is the creation or strengthening of the connections between events, in the impacts space and involving anthropogenic systems, that leads to our **terminology of 'connected' events as being distinct from 'compound' events**, and also from **interacting-risk** or **multi-risk** frameworks that focus on **combinations of physical hazards**.
Compound / Other	Pescaroli and Alexander (2018)	Compound Risk	Risk from: 1) **Extremes that occur simultaneously or successively**; 2) **Extremes combined with background conditions** that amplify their overall impact; or 3) **Extremes** that result from **combinations of "average" events**.
Compound / Other	De Ruiter et al. (2020)	Dependent Hazards (Triggering / Cascading)	Include **triggering and cascading disasters**, such as landslides triggered by a flood, or fires caused in the aftermath of an earthquake (Daniell et al., 2017). Cascading events are commonly defined as a primary hazard triggering a secondary hazard (Pescaroli & Alexander, 2015)
Compound / Other	Kappes et al. (2010); Kappes et al. (2012)	Cascading / Triggering Hazards	The **triggering of one hazard by another**, eventually leading to subsequent hazard events. This is referred to as **cascade, domino effect, follow-on event, knock-on effect, or triggering effect**.
Compound / Other	UNDRR (2019)	Cascading Hazard	**Cascading hazard** processes refer to a primary impact (trigger) such as heavy rainfall, seismic activity or unexpectedly rapid snow melt, followed by a **chain of consequences** that can cause secondary impacts
Compound / Other	Mishra et al. (2021)	Cascading / Compound Extreme Event	A **cascading (compound) event** occurs due to the **combination of two or more individual extreme events occurring successively (simultaneously)**. Examples of cascading events are: (a) a severe drought event followed by an extreme flood (drought-flood regime), and (b) an extreme drought followed by wildfire (drought-wildfire regimes), which can be further compounded by flooding events. The compound event can also be a combination of human and natural related disasters (Mishra et al., 2021).
Compound / Other	Cutter (2018)	Compound / Cascading / Triggering Hazard	Natural scientists working in the hazards arena inherently understand the **compounding physical processes and interactions that trigger a natural hazard event** such as an earthquake and follow on sequences of other events that occur as a direct or indirect result of the initial triggering event. **Compounding interactions** can trigger a secondary hazard (e.g., lightning causing a wildfire) or increase the probability of a hazard (e.g., wildfire destroying slope vegetation and when rain events occur mudflows ensue). **Compounding interactions are both spatially and temporally coincident and can amplify the effects**, especially if they occur over relatively short time periods and overlap geographically. **Compounding processes, compounding events, or compounding hazards** are synonyms for describing these types of processes or outcomes. **Cascading hazards** occur as a direct or indirect result of an initial hazard. One characteristic feature of cascading natural events is proximity in time and space, suggesting that there are sufficient

			forces or energy in the initial event to trigger the subsequent events in the physical system.
Compound / Other	Pescaroli and Alexander (2015)	Cascading Disasters	**Extreme events**, in which **cascading effects** increase in progression over time and generate unexpected secondary events of strong impact. These tend to be at least as serious as the original event, and contribute significantly to the overall duration of the disaster's effects. In cascading disasters, **one or more secondary events can be identified and distinguished** from the original source of the disaster.
Compound / Other	De Ruiter et al. (2020)	Consecutive Disasters	**Two or more disasters that occur in succession**, and whose direct impacts overlap spatially before recovery from a previous event is considered to be completed. This can include a broad range of **multi-hazard types**, such as **compound events** (Zscheischler et al., 2018) and **cascading events** (Pescaroli & Alexander, 2015). **Consecutive disasters** can occur due to dependency between natural hazards (e.g., **triggering events**) or when **independent hazards** occur in the same space-time window
Compound / Other	Pescaroli and Alexander (2018)	Interacting / Interconnected Risk	Risk from **physical dynamics** that develop through the existence of a widespread network of causes and effects, tends to overlap with **compound risk** in the hazard domain. Focus on the area in which hazard interacts with vulnerability to create disaster risk.
Compound / Other	Pescaroli and Alexander (2018)	Cascading Risk	Risk from '**toppling dominoes**' or '**systematic accidents'**. Associated mostly with the anthropogenic domain and the vulnerability component of risk.

Table 1. Examples of different compound event (and related) terminologies, types, and definitions in scientific literature. Unique aspects of varying definitions are emphasized in bold.

3) Flood Processes and Mechanisms

Having considered the compound event definitions, our second objective is to briefly discuss the key physical processes contributing to flooding and the individual drivers/hazards recognized in this review. In this review we focus on coastal regions. Here, flooding mainly arises from three main flood drivers, namely (i) fluvial, (ii) pluvial, and (iii) coastal. In this section we start by discussing these three drivers and their mechanisms individually (Section 3.1). It is these three drivers, in different combinations, that most often result in compound flood events. Schematic diagrams illustrating the varying flood processes associated with these three main drivers are shown in Figure 1. However, flooding can also arise from three less frequent auxiliary flood drivers, that is (iv) groundwater, (v) damming and dam failure, and (vi) tsunamis. These additional flood drivers are also briefly discussed (Section 3.2). Finally, we also highlight several precursor events and environmental conditions that can influence the magnitude and/or occurrence of flooding (Section 3.3).

3.1 Main Drivers of Flooding in Coastal Regions

Fluvial flooding (Figure 1a), also known as river (or riverine) flooding is induced by the accumulation of large volumes of excessive rainfall and snowmelt. Intense precipitation during extreme meteorological events (e.g., TCs/ETCs and atmospheric rivers) and weather seasons (e.g., monsoons) can inundate rivers quickly (Gori et al., 2020b). Elevated volumes of water cause the level in rivers, creeks, and streams to rise above their channel banks and spill out into the adjacent low-lying area known as the floodplain. Thus, fluvial flooding depends on topography, hydrometeorological conditions, and catchment characteristics (e.g., size, shape, slope, land cover, and soil properties) (Harrison et al., 2022). The peak of river flooding can have a time lag of hours to weeks between the rainfall over a catchment and the exceedance of downstream channels (Valle-Levinson et al., 2020). In the spring, fluvial flooding can also be driven by snowmelt (or glacial melt) as large reservoirs of melting freshwater flow into downstream river channels (Melone, 1985; Benestad and Haugen, 2007). Freshwater fluvial flooding occurs worldwide but is more frequent in high latitude (e.g., Canada and Northern Europe) and high elevation (e.g., Hindu Kush and Andes Mountains) regions.

Pluvial flooding (Figure 1b) is the result of intense rainfall (flash flooding) or long-sustained moderate rainfall. As the rain reaches the ground, flooding occurs when the soil becomes fully saturated and can no longer absorb water (saturation excess) and/or the infiltration capacity is overwhelmed (infiltration excess) (Bronstert et al., 2023), causing ponding and surface runoff (overland flooding) that flows down terrain and into rivers (in practice the boundary between pluvial and fluvial flooding is not well defined and is usually based on catchment area rather than physical process). Urban flooding is closely linked with pluvial flooding where excessive runoff in areas of human development has insufficient drainage, often due to impervious surfaces such as concrete and asphalt (Gallien et al., 2018; Bronstert et al., 2023). Urban flooding also ties in with sewer and stormwater flooding in which pluvial surface runoff infiltrates waste management infrastructure and exceeds drainage system capacity (Mark et al., 2004; Archetti et al., 2011; Gallien et al., 2018; Meyers et al., 2021).

Coastal flooding (Figure 1c) mainly occurs from one or more combinations of high astronomical tides, storm surge, and wave action (runup, set up, swell, seiche), superimposed on relative mean sea level (Pugh, 1987; Haigh and Nicholls, 2017). Each of these components of total sea level contributes differently to flooding, but we have chosen to group them together for simplicity. Coastal flooding primarily refers to flooding at the interface of land and ocean; however, it is sometimes also used when discussing instances of flooding by these mechanisms (e.g. seiche) along the shoreline of lakes (Stevens and Lawrence, 1997). Tides are the regular and predictable rise and fall of the sea level caused by the gravitational attraction and rotation of the Earth, Moon, and Sun. Tides exhibit diurnal, semi-diurnal, or mixed diurnal cycles and experience shifts in amplitude on fortnightly, bimonthly, and interannual timescales (Pugh, 1987; Haigh et al., 2020). Storm surges are driven by storm events with low atmospheric pressure that cause sea levels to rise, and strong winds that force water towards the coastline. Storms also generate waves, locally or remotely (e.g., swell), via the interaction of wind on a water's surface due to boundary friction and energy transfer. Waves mostly contribute to enhanced coastal flooding via setup (the increase in mean water level due to the presence of breaking waves) and runup (the maximum vertical extent of wave uprush on a beach or structure)(Phillips, 1966). Mean sea level is the average height of the sea after filtering out the short-term variations associated with tides, storm surges, and waves. Increases in relative mean sea level arise as a result of vertical land movements (i.e., isostatic SLR) and changes in ocean volume (i.e., eustatic SLR) from thermal expansion of water, mass loss from glaciers and polar ice sheets, and changes in terrestrial water storage (Oppenheimer et al., 2019).

3.2 Other Drivers of Flooding

In Section 3.1 we considered the three main flood drivers, which most frequently contribute to compound flooding in coastal regions. However, other less frequent drivers can also play an important role in compound floods and are briefly summarised below. Groundwater flooding is the rise of the water table to the ground surface or an elevation above human development (Holt, 2019). This occurs during an increase in the volume of water entering an underlying aquifer. This can be the result of prolonged rainfall and snowmelt, but in the case of unconfined coastal aquifers can also be driven by SLR and saltwater intrusion (Plane et al., 2019; Befus et al., 2020; Rahimi et al., 2020). Groundwater flooding is often observed along shorelines that are equal to or below sea level (Plane et al., 2019; Befus et al., 2020; Rahimi et al., 2020), in regions with high ground-surface connectivity (Jane et al., 2020), and in areas experiencing ground subsidence (downward vertical shift of Earth’s surface from processes such as compaction and groundwater extraction) (Rozell, 2021). As coastal groundwater flooding is the result of long-term changes, it is slow to dissipate and usually persists longer than floods driven by fluvial and pluvial processes (Rozell, 2021).

Damming and dam failure (whether occurring naturally or from anthropogenic activities) can result in flooding from a rapid release or build-up of large volumes of water. Natural damming including beaver dams, ice jams, volcanic dams, morainal dams, and landslide dams can inhibit flow and cause backwater flooding (and even lake formation) (Costa, 1985). Anthropogenic damming is the intentional inundation (via impoundment) of a hydrological network for purposes of resource management (Baxter, 1977). Natural dam failures such as glacial outbursts and landslide dam overtopping can release vast quantities of water that overwhelm and inundate downstream landscapes (Costa, 1985). The failure of human-engineered water control infrastructure (e.g., dams, levees, dykes, water supply systems) can also cause substantial downstream flooding; often posing a greater threat due to the close proximity to human development (e.g., 2017 Oroville Dam crisis (Koskinas et al., 2019) and 2023 Derna dam collapses (Reliefweb, 2023)).

Tsunamis are a series of impulsive waves generated by the sudden displacement of large volumes of water due to undersea earthquakes and landslides, shifts in the tectonic plates, and underwater volcanic eruptions (Iotic, 2020). While large-magnitude tsunami events occur infrequently compared to other flood drivers, they still have the potential to cause catastrophic flooding in coastal regions. Tsunamis are also unique in their potential to drive coastal flooding at oceanic scales, sometimes spanning multiple countries and continents (e.g., 2004 Indian Ocean Tsunami (Lavigne et al., 2009; Leone et al., 2011) and 2022 Hunga Tonga Tsunami (Manneela and Kumar, 2022; Borrero et al., 2023)).

3.3 Precursor Events and Environmental Conditions

In addition to the aforementioned six flood drivers, we also bring to attention five important precursor events and environmental conditions that can strongly influence flooding and whether or not it occurs. First, high anomalous and antecedent soil moisture conditions commonly exacerbate surface flooding due to reduced soil drainage capacity and infiltration (Ganguli et al., 2019; Stein et al., 2019). Elevated freshwater volumes from snowmelt may escalate fluvial and groundwater flooding (Melone, 1985; Benestad and Haugen, 2007; Vormoor et al., 2015). Extreme temp/heat increases precipitable atmospheric water content via elevated relative humidity, as well as amplify the rate of snowmelt; thus intensifying both pluvial and fluvial flooding respectively (Berghuijs et al., 2019; Bermúdez et al., 2021). Wildfires can worsen pluvial and fluvial flooding by modifying soil properties such that ash deposits and burnt hydrophobic soils cause rapid surface flows and channelization (Bayazıt and Koç, 2022; Jong-Levinger et al., 2022; Belongia et al., 2023; Xu et al., 2023). Finally, drought is known to potentially intensify pluvial flooding when long-term water deficiencies dry out and harden the soil, in turn reducing ground infiltration and amplifying surface flows (Katwala, 2022). Prolonged drought, wildfire, and extreme heat each lead to vegetation loss, resulting in reduced surface roughness and consequently more intense overland flow. We note that many of these precursors and conditions have partially overlapping influences on flooding as they are inherently interlinked by shared climatic and meteorological forcings.

4) Literature Database Methodology

Our third objective is to develop a database of the extensive English-written scientific literature on compound flood research. In this section we describe how the database was compiled, and then we review and discuss the database contents in objectives four (Section 5) and five (Section 6).

A combination of *systematic review* and *content analysis* was used to collect scientific literature and filter for publications relevant to the scope and themes of this paper. Published journal articles, academic theses, conference proceedings (but not conference abstracts), as well as government and scientific reports up to and including the year 2022 were sourced using the Web of Science, Semantic Scholar, Google Scholar, and Dimensions AI database search engines. Papers were filtered by topic, title, abstract, and full text (when possible) entering different combinations of key search terms as shown in Table 2. Potential valid articles were also identified from the bibliographies of compound flood papers using literature mapping tools, including Connected papers, Citation Gecko, Local Citation Network, and Open Knowledge Maps. Research literature was then screened for relevance based on the set of criteria defined below. See Figure A1 for a PRISMA flow diagram of literature curation.

To be included in this review, applicable papers must:

1) focus primarily on compound flooding, and not simply mention it fleetingly in the abstract or conclusion when in fact addressing univariate flooding;
2) involve multivariate statistical analysis, numerical modelling (hydrological and/or hydrodynamic), and/or discussion of two or more flood drivers, precursors events, or environmental conditions, of which at least one being one of the main three flood drivers (fluvial, pluvial, coastal); and
3) take place in coastal regions, (i.e. near an ocean, sea, inlet, estuary, or lake)

Papers deemed appropriate were added to the literature review database and categorized by:

1) case study geographic scope;
2) case study scenario;
3) flood drivers, precursor events, and/or environmental conditions considered;

4) research approach (numerical modelling, statistical modelling/analysis, or both); and

5) study application (earth system processes, risk assessment, impact assessment, forecasting, planning and management, and methodological advancement).

Search Terms
“compound* flood*”
“joint* flood*”
“coincid* flood*”
“comb* flood*”
“multivariate flood*”
“multi* flood*”
“multi-hazard” AND “flood*”
“cascading” AND “flood*”
“trigger*” AND “flood*”
“concurrent” AND “flood*”
“precondition” AND “flood*”
“antecedent” AND “flood*”
“*connected” AND “flood*”
“consecutive” AND “flood*”
“simultaneous” AND “flood*”
(“cooccur*” OR “co-occurr*”) AND “flood*”
(“interrelat*” OR “interact*”) AND “flood*”
(“joint probability” OR “joint occurrence”) AND “flood*”
(“river” OR “discharge”) AND (“precipitation” OR “rain”) AND “flood*”
(“precipitation” OR “rain”) AND (“surge” OR “tide” OR “wave”) AND “flood*”
(“river” OR “discharge”) AND (“surge” OR “tide” OR “wave”) AND “flood*”
“fluvial” AND “pluvial” AND “flood*”
“fluvial” AND “coastal” AND “flood*”
“pluvial” AND “coastal” AND “flood*”
“fluvial” AND “pluvial” AND “coastal” AND “flood*”

Table 2. Literature database keywords and Boolean search terms. Asterisks act as multi-character wildcards used to capture alternative phrasing of truncated root words (e.g., ‘flood’ returns ‘flood-s’, ‘flood-ed’, and ‘flood-ing’)*

To fully clarify the scope of this review, we again emphasize that this review is focused on compound flood literature in coastal (ocean/lake) and estuarine environments. Some may argue that all coastal flooding (or really flooding in general) involves a combination of multiple drivers. While this is not untrue, the majority of historical flood and coastal flood literature has not explicitly focussed on the compounding interactions between the different components of flooding, and how those interactions influence flooding as a whole. For this reason, general coastal flood literature that does not explicitly examine the interactions of different flood mechanisms on total flooding is excluded. Additionally, while compound flood literature must examine flooding in coastal and estuarine regions, it does not necessarily require the consideration of coastal drivers to be included (e.g. compound fluvial-pluvial flooding at the coast). Finally, we highlight that historical literature that does not use the phrase “compound flood" may still be included as they would have satisfied the other keyword search terms listed in Table 2.

Keeping in line with the compound event definition framework outlined in Section 2, and the individual flood mechanisms detailed in Section 3, this review recognizes compound flooding as a combination of two or more of the six flood drivers (fluvial, pluvial, coastal, groundwater, damming/dam failure, and tsunami) and five precursor events and environmental conditions (soil moisture, snow, temp/heat, fire, and drought). In this paper, the coastal driver category will encapsulate processes at lake coasts in addition to oceanic coasts, as lakes exhibit wind-driven oscillating waves (seiche) that contribute to compound flooding similarly to oceanic tide and storm surge. Not considered in the review are studies that assess the cooccurrence or consecutive occurrence of flood characteristics that are not unique to a particular flood driver variable (e.g., flow velocity, flood volume, flood duration, flood intensity, flood depth/height). Additionally, this review does not recognize the confluence or convergence of river channels within the same river network as compound flooding. While there is considerable literature on this subject (e.g., Bender et al. (2016)), fluvial-fluvial compounding predominantly occurs inland and therefore is not included within the scope of this paper, which we again emphasize focuses on coastal regions. This review does however recognize the compounding of like-type flood drivers in the case of pluvial-pluvial temporal clustering as well as coastal-coastal between different coastal components (e.g., tide-surge, surge-waves, or tide-waves).

While this review aims to provide an overview of existing research on compound flooding, it is necessary to recognize the limitations of the literature review database. Most notably, this review only considers English-written scientific literature and thus may not fully represent the perspectives and findings of all research communities. Throughout the literature database development process, a small number (<5) of non-English compound flood studies were identified but omitted to preserve consistent methodology. Similarly, ~10 coastal compound flood papers were identified but inaccessible from the publisher. The final literature database used in this study is extensive but not exhaustive, as some compound flood literature may have been overlooked or excluded based on the drivers, precursor events, and environmental conditions in the review's scope.

From these literature search and database curation methodologies, we obtained a total of 279 compound flood publications. A detailed overview of the compound flood literature database is presented in the Appendix (Table A1).

5) Review of Literature Database

The fourth objective of the review is to identify and reflect on trends in the characteristics of compound flood research. We discuss general bibliometric characteristics of compound flood literature including: publications over time (Section 5.1), the geographic scope of compound flood case studies (Section 5.2), and the key scientific journals and/or institutions (Section 5.3). We then review the flood drivers considered (Section 5.4), the analytical approaches applied in the studies (Section 5.4), and their various research applications (Section 5.5).

5.1) Publications by Year

As mentioned previously, we identified 279 publications on compound flooding up to and including the year 2022. The number of publications per year identified in the review is shown in Figure 2. Up until the year 2000 there were very few compound flood studies (17) (Rossiter, 1961; Myers, 1970; Ho and Myers, 1975; Prandle and Wolf, 1978; Mantz and Wakeling, 1979; Walden et al., 1982; Loganathan et al., 1987; Chou, 1989; Vongvisessomjai and Rojanakamthorn, 1989; Flick, 1991; Tawn, 1992; Acreman, 1994; Coles and Tawn, 1994; Dixon and Tawn, 1994; Jones, 1998; Coles et al., 1999; Rodríguez et al., 1999), with the earliest being Rossiter (1961). Since then, there has been a considerable increase in compound flood related papers. The past three years (2020-2022) in particular have spawned a considerable number of compound flood papers (133), nearly half (48%).

5.2) Publications by Geographic Region

The number of compound flood related papers, organized by geographical region on which the study focuses, are displayed in Figure 3a, and spatially mapped in Figure 3b. Although there has been increasing focus on the compound nature of flooding, the spatial scope of compound flood research is largely limited to a few geographic regions. Nearly half the publications are directed at compound flooding along the US coastlines (114, 40%). The spatial distribution of US-related studies is visualized in Figure 3c. Following the US, some of the next most frequently studied regions are the UK (36, 13%), China (20, 7.1%), Global (12, 4.3%), Europe (12, 4.3%), Australia (9, 3.2%), the Netherlands (8, 2.8%), Canada (8, 2.8%), and Taiwan (7, 2.5%). Additional geographic regions assessed in <7 studies are presented in Figure 3a.

5.3) Publications by Journals and Institutions

A total of 115 unique scientific journals and institutions (i.e., universities and government agencies) have published compound flood research (i.e., articles, reports, proceedings, and theses). More than half (141, 51%) of the compound flood literature is published in 15 academic research journals (Figure 4), with the top 5 most frequent journals being Natural Hazards and Earth System Sciences (26, 9.3%), Journal of Hydrology (14, 5.0%), Hydrology and Earth System Sciences (11, 3.9%), Water Resources Research (10, 3.6%), and Water (10, 3.6%). Although a considerable volume of compound flood research is published by a select few journals and institutions, a total of 71 journals and institutions have only published a single compound flood study. We suspect that this will change in the years to come as the field of compound flood hazards gains further attention.

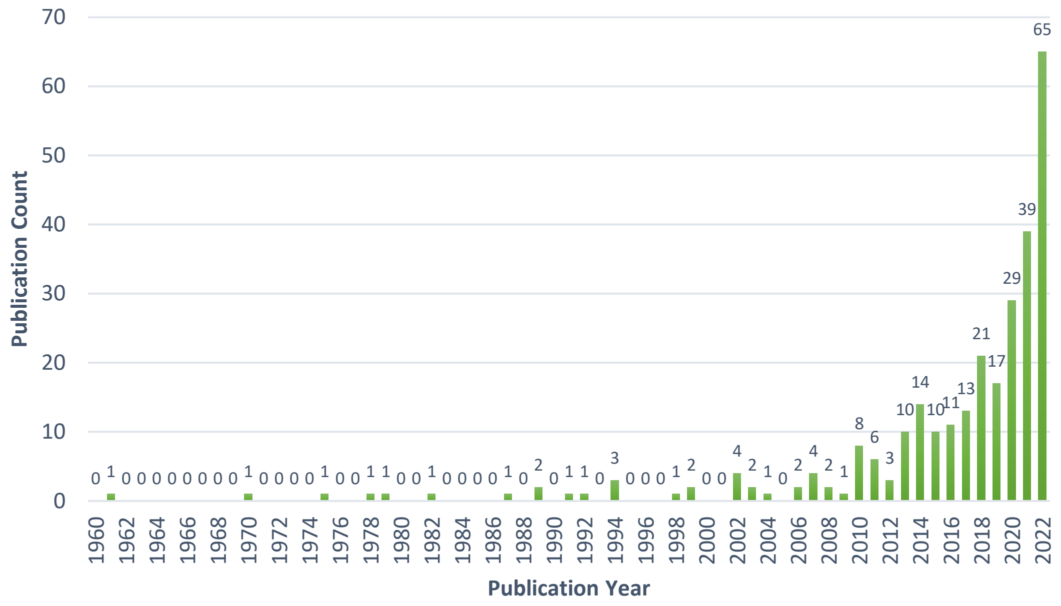
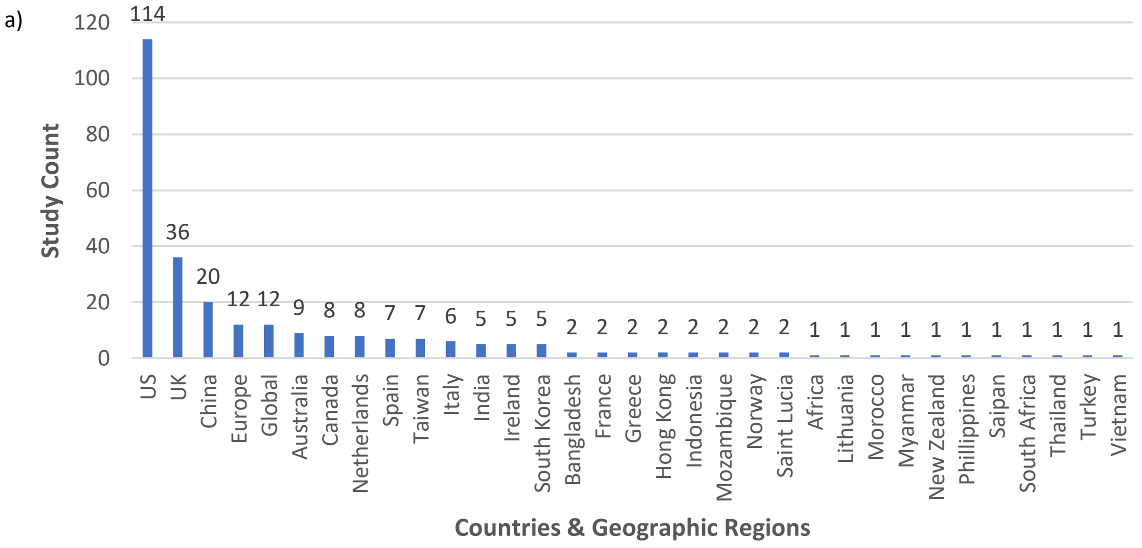


Figure 2. Histogram showing compound flood literature review database publications over time from 1960 to 2022.



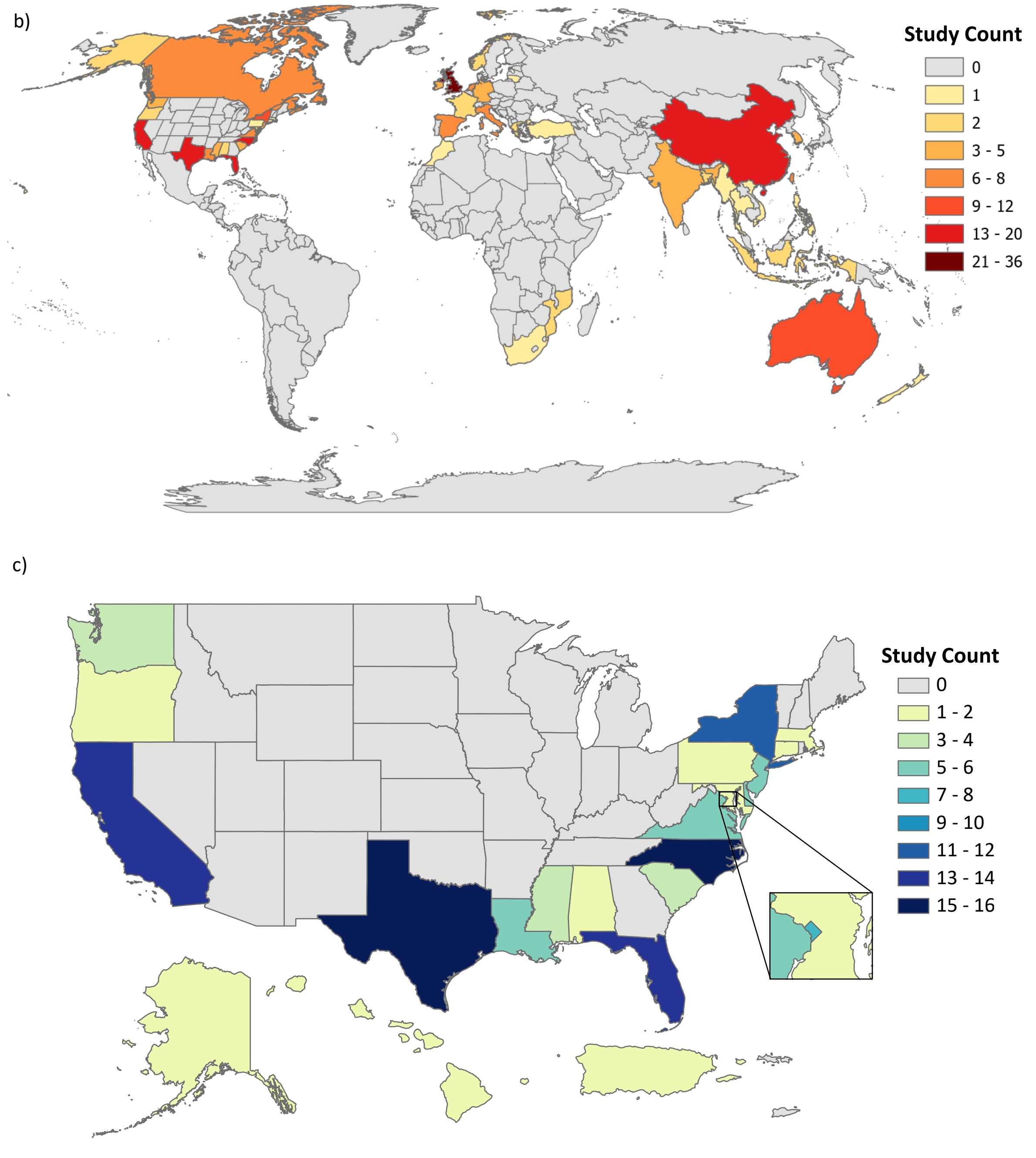


Figure 3. (a) Histogram showing the geographic frequency of compound flood case study regions; and geographic maps showing the frequency of compound flood case study sites (b) across the world (excluding global studies) and (c) throughout the United States (including Alaska, Hawaii, Puerto Rico, and Washington DC).

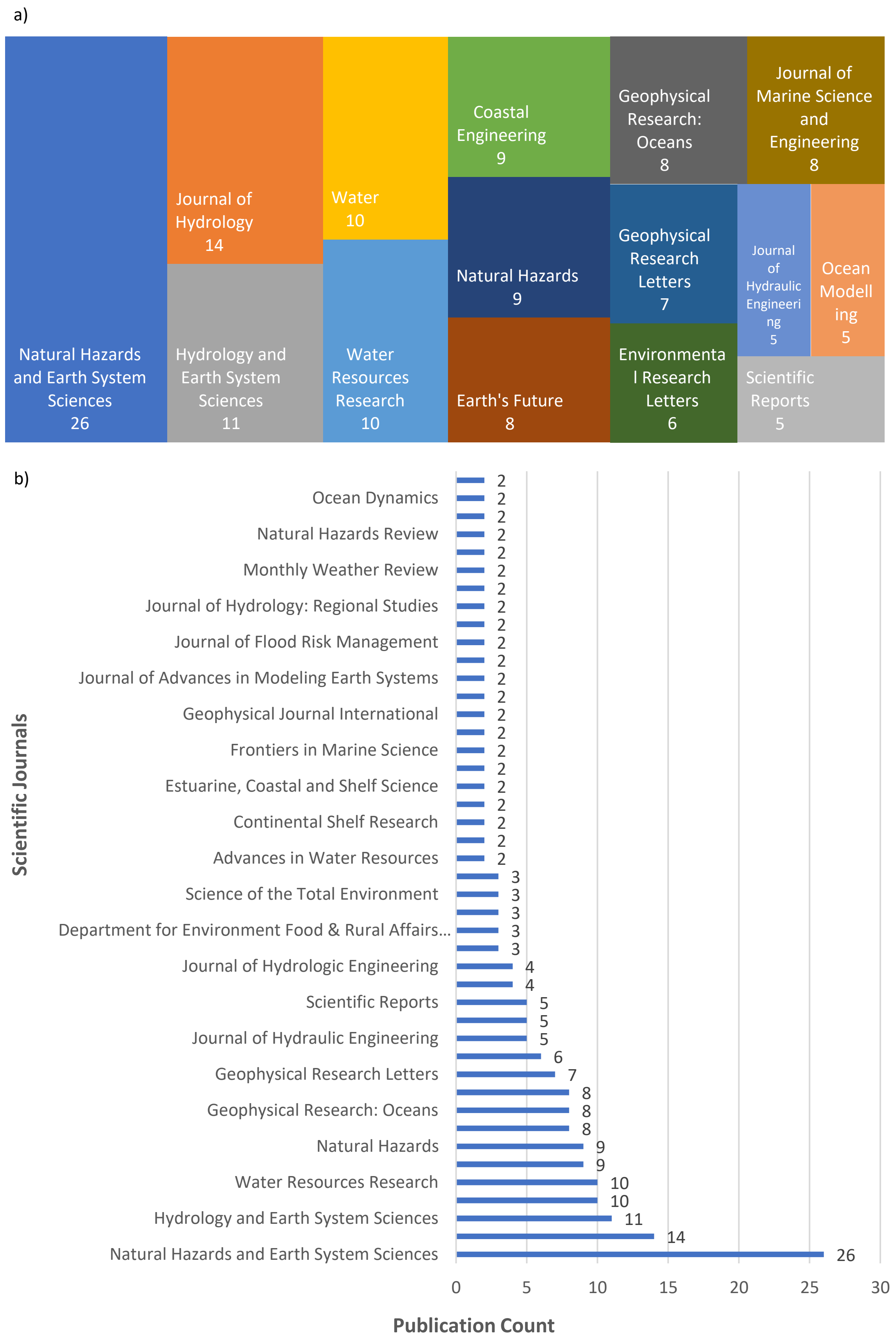


Figure 4. (a) Treemap of the top 15 most frequent scientific journals and/or institutions that have published compound flood research; and (b) histogram of scientific journals and/or institutions that have published at least two compound flood papers.

5.4) Review of Flood Drivers Considered

Across the 279 studies in the review database, a total of 11 unique compound flood drivers, precursor events, and environmental conditions were identified. These are listed in Table 3 and visualized in Figure 5. Due to the highly complex interactions between terrestrial, oceanic, and atmospheric systems, most studies choose to limit the scope of their research to a select few flood-driving mechanisms. For instance, some focus on TC/ETC and extreme precipitation events, while others address elevated river discharge in tandem with storm surge. Looking at the combination of drivers analysed, 44 (16%) studies considered exactly the three main components of compound flooding (fluvial, pluvial, coastal); note that analysis of three drivers does not necessarily dictate trivariate analysis (e.g., fluvial-pluvial-coastal), but can also describe two separate bivariate analyses (e.g., fluvial-coastal and pluvial-fluvial) that together include three drivers. The remainder of the studies largely considered combinations of the main drivers (often as bivariate analyses), the most prominent being fluvial-coastal (84, 30%), pluvial-coastal (80, 29%), and coastal-coastal (38, 14%) (e.g., surge and tide) (Figure 5). These results are to be expected as compounding is most prevalent at the coast. A select few examples of unique and less frequently studied compound flood driver combinations include, pluvial-snow (Lawrence et al., 2014), pluvial-fire (Cannon et al., 2008; Bayazıt and Koç, 2022; Jong-Levinger et al., 2022), coastal-tsunami (Kowalik and Proshutinsky, 2010; Zhang et al., 2011), pluvial-temp/heat (Benestad and Haugen, 2007), pluvial-drought (Ridder et al., 2020), pluvial-coastal-damming/dam failure (Kim and Sanders, 2016), and coastal-groundwater (Habel et al., 2020).

Flood Drivers, Precursors Events, and Environmental Conditions	Number of Studies in which Considered	Other Corresponding Terms & Variables
Coastal	259 (93%)	tide, astronomical tide, storm-tide, surge, storm surge, swell, storm swell, waves, sea surface height, sea level, ocean level, sea water level, total sea level, non-tidal residuals, NTR, H, S, T, W
Pluvial	154 (55%)	precipitation, flash flood, rainfall, rainfall-runoff, rainfall anomalies, rainfall extremes, surface runoff, surface inundation, P
Fluvial	143 (51%)	river discharge, riverine discharge, riverine flow, streamflow, streamflow discharge, river level, fluvial discharge, channel discharge, channel flow, Q, R
Groundwater	5 (1.8%)	water table, groundwater level, groundwater head
Soil Moisture	5 (1.8%)	soil saturation, soil moisture extremes, soil moisture anomalies, antecedent soil moisture
Fire	3 (1.1%)	wildfire, forest fire
Damming/Dam Failure	2 (0.72%)	dam, levee, barrier, wall, reservoir; dam breach, dam failure, dyke breach, dyke failure, levee breach, levee failure, reservoir breach, reservoir failure
Temp/Heat	2 (0.72%)	temperature extremes, temperature anomalies, extreme heat,
Snow	2 (0.72%)	snowmelt, snowfall, glacial melt, freshwater melt
Tsunami	2 (0.72%)	--
Drought	1 (0.36%)	--

Table 3. List of unique flood drivers, precursor events, and environmental conditions (plus terms and variables) observed in compound flood research from the literature review database.

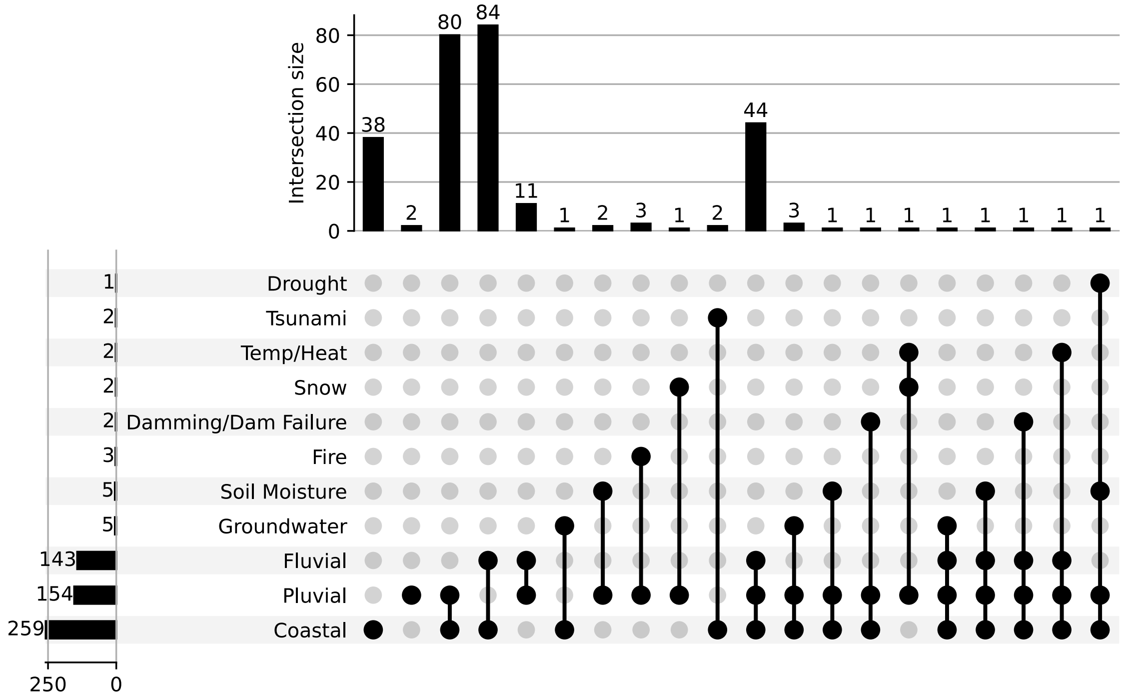


Figure 5. UpSet plot (Lex et al., 2014) visualizing the combinations and frequency of driver multi-classifications assigned across the literature. The vertical histogram presents the total count of studies considering each of the eleven drivers (plus precursor events and environmental conditions) categorized nonexclusively, while the horizontal histogram presents the total count for each driver multi-classification combination exclusively. Flood driver classifications for like-type compounding (i.e., pluvial-pluvial and coastal-coastal) are indicated by a non-linked circle. Note that analysis of three drivers does not necessarily dictate trivariate analysis (e.g., fluvial-pluvial-coastal). It may instead describe two separate bivariate analyses (e.g., fluvial-coastal and pluvial-fluvial) as part of the same study that together consider three drivers.

5.5) Review of Research Approaches

Across the database, the compound flood studies have tended to apply approaches that generally fall into two categories: (1) physical (process-based) numerical modelling, and/or (2) statistical modelling and analysis; similar findings to that of Tilloy et al. (2019). The number of studies applying each approach is illustrated in Figure 6. In total, 102 (36%) studies used only numerical modelling approaches, 95 (34%) used only statistical approaches, and 80 (29%) studies applied hybrid methods involving a combination of numerical and statistical approaches. Within the main two approach classes are many different methods for investigating compound floods, each of which exhibits its own benefits and limitations as discussed in Section 6. Lastly, 2 (<1%) studies used neither of these approaches, instead completing qualitative survey-based investigations related to the perception and understanding of compound flooding by disaster managers and the wider public (Curtis et al., 2022; Modrakowski et al., 2022).

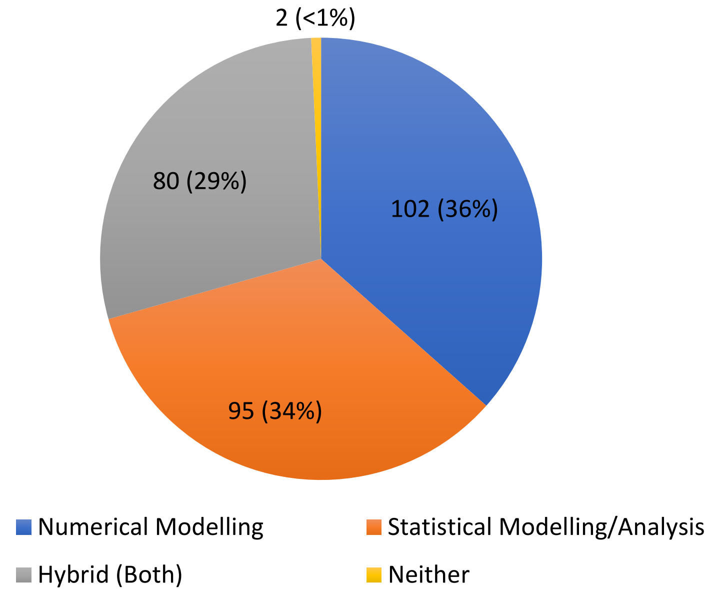


Figure 6. Pie chart showing the proportion of compound flood literature review database studies that implement numerical modelling, statistical modelling/analysis, hybrid (both) methods, and neither of the two approaches.

5.6) Review of Research Applications

Across the database, the compound flood studies have tended to relate to six main application themes, as illustrated in Figure 7. Assessing the individual research application categories nonexclusively, 130 (47%) studies consider Earth System Processes, 129 (46%) Risk Assessment, 11 (3.9%) Impact Assessment, 21 (7.5%) Forecasting, 28 (10%) Planning & Management, and 80 (29%) Methodological Advancement (Figure 7). These applications are discussed in more detail in Section 6.7. Reflecting on the exclusive multi-classification of applications, the three most common classifications are 'Earth System Processes' (74, 27%), 'Risk Assessment' (50, 18%), and 'Methodological Advancement' (31, 11%) which together account for over half of the literature database entries (Figure 7). This is to be expected as they are the broadest of application categories, but also the primary objective of most research. Other prominent research application classification categories include 'Earth System Processes, Risk Assessment' (30, 11%); 'Methodological

Advancement, Risk Assessment' (22, 7.9%); 'Earth System Processes, Methodological Advancement' (19, 6.8%); and 'Planning & Management, Risk Assessment' (12, 4.3%) (Figure 7).

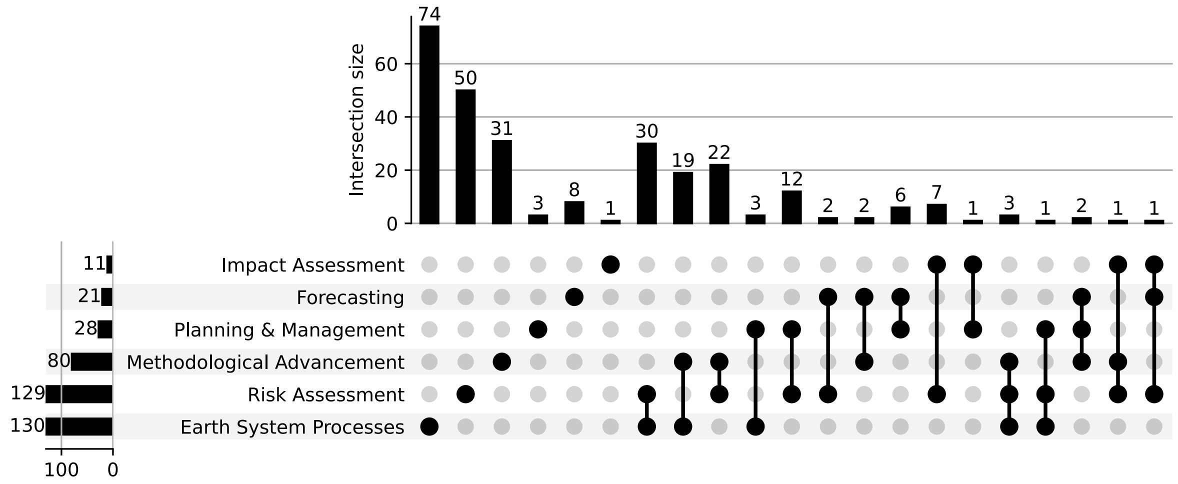


Figure 7. UpSet plot (Lex et al., 2014) visualizing the combinations and frequency of application multi-classifications assigned across the literature. The vertical histogram presents the total count of studies considering each of the six application categories non-exclusively, while the horizontal histogram presents the total count of each application multi-classification combination exclusively. Instances of single application classification are indicated by a non-linked circle.

6) Discussion

Our fifth objective is to synthesize the key findings (e.g., dependence hotspots and driver dominance), considerations (e.g., uncertainty and climate change), and standard practices (e.g., application cases and analytical methods) of the compound flood research from across the database. First, we examine the global and regional hotspots of compound flooding, outlining where and when different driver pairs exhibit significant dependence (Section 6.1). Next, we discuss the tendency for certain drivers to dominate the compound flooding process and examine how this changes spatially as influenced by landscape characteristics (Section 6.2). We then consider compound flooding in the context of urban and coastal infrastructure and how these environments are particularly susceptible to the compounding drivers as it is a common consideration throughout the literature (Section 6.3). Next, we assess how climate change is expected to affect the frequency, variability, and severity of compound flooding in the future (Section 6.4). Then, we reflect on the different approaches that have been used in the literature to analyse compound flooding (Section 6.5). Finally, we investigate the range of different applications considered across the literature (Section 6.6).

6.1) Compound Flood Hotspots and Spatiotemporal Dependence Patterns

Our review highlights that knowledge of compound flooding hotspots, spatiotemporal patterns, and multivariate dependence characteristics has advanced considerably in recent years. However, the ways in which global meteorological and climate modulators affect the propensity of compound flooding in one region over another are not fully understood, and few studies consider the non-stationarity of multivariate flood variable dependence. Nonetheless, large-scale patterns in the seasonal and interannual occurrence of compound events have become apparent in several regions (Wu et al., 2018; Ganguli and Merz, 2019a, b; Ridder et al., 2020; Lai et al., 2021a; Lai et al., 2021b; Camus et al., 2022; Stephens and Wu, 2022).

Existing compound event literature has identified certain areas around the world that are especially prone to compound flooding, namely: Southern Asia, where monsoon floods and cyclones cause widespread damage; the Gulf and East Coasts of the United States, where hurricanes induce storm surge and intense rainfall which exacerbate pluvial and/or fluvial flooding; global low-lying delta regions (e.g., Ganges, Irrawaddy, Mekong, Mississippi, Rhine, and Pearl) where riverine and coastal waters together induce severe flooding; northern and western Europe which are prone to river flooding plus extreme precipitation and surge from storm events; and coastal areas of East Asia, Southeast Asia, and Oceania, where TCs/ETCs drive joint fluvial and coastal flooding (Apel et al., 2016; Ikeuchi et al., 2017; Bevacqua et al., 2020a; Couasnon et al., 2020; Eilander et al., 2020; Camus et al., 2021; Lai et al., 2021a). Below we further detail the spatiotemporal patterns in compound flooding and driver interdependence by region.

North America: The coasts of North America are the most studied in terms of compound flooding globally. Compound flooding predominantly occurs along the mid-eastern US coastline and the Gulf of Mexico due to TCs/ETCs that generate heavy rainfall and extreme sea levels (Ridder et al., 2020; Camus et al., 2021; Najafi et al., 2021; Camus et al., 2022). Joint pluvial-fluvial extremes account for the majority of compound flood events and occur frequently with low return periods (<0.5 years) over the entire contiguous US, particularly along the coasts (Ridder et al., 2020). Coastal-fluvial drivers too exhibit positive dependence on both coasts (Ridder et al., 2020). Dependence is also measured between flood drivers along Canada's coasts, albeit less frequent relative to the US (Jalili Pirani and Najafi, 2020). Throughout the Great Lakes, consistent significant positive dependence is found between pluvial-coastal drivers. On the east coast, pluvial-fluvial extremes are frequent in late spring and early summer during the Atlantic hurricane season (Ridder et al., 2020; Nasr et al., 2021). This region exhibits strong correlations between pluvial-coastal (Wahl et al., 2015; Lai et al., 2021a) and fluvial-coastal (Moftakhari et al., 2017) drivers (Camus et al., 2021; Nasr et al., 2021). Lastly, the west coast features positive dependence for fluvial-coastal (Ward et al., 2018) and pluvial-coastal (Lai et al., 2021a) pairs during the winter ETC season (Nasr et al., 2021).

Central & South America: Current knowledge of compound flood events in Central and South America is lacking due to a void of localized research. Global studies on compound flooding indicate that fluvial-pluvial extremes are the most frequent cause of compound flooding in South America; and largely occur in the eastern half of the continent (particularly Brazil) during austral summer/late autumn (Ridder et al., 2020). Similarly, there is a positive dependence between fluvial-coastal flood drivers on the southeast coast of Brazil, with large clustering in the highly populated states of São Paulo and Rio de Janeiro (Ward et al., 2018; Couasnon et al., 2020; Ridder et al., 2020). On the west coast, co-occurring fluvial-coastal extremes are located in the southern portion of Chile in austral summer (Couasnon et al., 2020; Ridder et al., 2020).

Europe: Across Europe, large-scale low-pressure systems are a prominent modulator of compound floods (Ridder et al., 2020), with most (~90%) events (Camus et al., 2021) occurring in the winter ETC season (Ridder et al., 2020; Lai et al., 2021a; Camus et al., 2022). The main hotspots of compound flooding are the west coast of the UK, the northwest coast of the Iberian Peninsula, around the Strait of Gibraltar, coasts along the North Sea, and the eastern portion of the Baltic Sea (Ward et al., 2018; Couasnon et al., 2020; Ridder et al., 2020; Camus et al., 2021). Concomitant pluvial-fluvial and pluvial-coastal extremes are most prominent in western Europe (Couasnon et al., 2020; Ridder et al., 2020; Camus et al., 2021; Lai et al., 2021a). In Ireland and the UK, joint occurrence of high skew surges and high river discharge are more common on the west and southwest coasts compared to the east coast (Svensson and Jones, 2002, 2004; Ward et al., 2018; Hendry et al., 2019; Camus et al., 2021). Pluvial-fluvial drivers also show strong positive correlations in southern Italy, the east coast of Turkey, the eastern Mediterranean, the coasts along the North Sea, and parts of the Baltics. Compound rainfall and river discharge occur primarily in the early summer to late autumn. For fluvial-coastal and pluvial-coastal driver dependence, there are strong correlations along the Iberian coasts, the Strait of Gibraltar, and the UK west coast (Svensson and Jones, 2003; Svensson and Jones, 2004; Ward et al., 2018; Camus et al., 2021; Lai et al., 2021a). Lastly, positive pairwise dependence of temporally compounding pluvial-pluvial (“wet-wet”) conditions is prominent along the coastal Mediterranean (De Michele et al., 2020).

Africa: Research in Africa is sparse relative to the other continents; however, a few compound flood patterns have been ascertained along the northern, southern, and eastern coasts. Portions of northern Africa show significant positive pluvial-fluvial correlation along the southern Mediterranean and eastern Atlantic coasts including Libya, Tunisia, Algeria, and especially Morocco (Camus et al., 2021). Morocco has the greatest compound flood potential in northern Africa as it also demonstrates strong dependence for coastal-pluvial (Zellou and Rahali, 2019) and coastal-fluvial extremes (Camus et al., 2021). Analysis of rain gauges across northern Africa also reveals a select few sites in Algeria with pluvial-pluvial (“wet-wet”) pairwise dependence (De Michele et al., 2020). In southern and eastern Africa, both South Africa and Mozambique experience compound flooding from seasonal TCs during austral summer (Bischiniotis et al., 2018; Ward et al., 2018; Couasnon et al., 2020; Ridder et al., 2020; Claassen et al., 2023). As a result, this region has strong dependence relationships between the flood driver pairs coastal-fluvial, coastal-pluvial, and pluvial-fluvial (Van Berchum et al., 2020; Eilander et al., 2022a; Kupfer et al., 2022). Lastly, Madagascar has significant positive coastal-fluvial dependence (Couasnon et al., 2020; Ridder et al., 2020) also due to its exposure to TCs (Claassen et al., 2023).

Asia: Compound flood spatiotemporal distributions are highly varied throughout Asia but tend to be most frequent in the south, southeast, and east. Strong correlations for fluvial-coastal extremes are seen at the coasts of India and Bangladesh (Bay of Bengal), Indonesia (North Natuna Sea), Vietnam (East Sea), Philippines (West/East Philippine Seas), Malaysia, China, Taiwan, and Japan (Sea of Japan) (Ikeuchi et al., 2017; Ward et al., 2018; Couasnon et al., 2020; Ridder et al., 2020; Leijnse et al., 2021; Pandey et al., 2021; Sampurno et al., 2022b). Similarly, there is positive dependence for pluvial-fluvial drivers in India, Bangladesh, and Japan (Ganguli et al., 2019; Ridder et al., 2020; Khatun et al., 2022; Claassen et al., 2023). Co-occurring pluvial-coastal extremes are most prominent in the wet monsoon season in east Asia (particularly China, Taiwan, and Japan)(Lai et al., 2021a; Lai et al., 2021b), southeast Asia (Lu et al., 2022), and south Asia (Vongvisessomjai and Rojanakamthorn, 1989; Shahapure et al., 2010; Mohanty et al., 2020). Most compound flood events within Asia occur from summer to late autumn, corresponding with the TC/ETC seasonality in the western Pacific.

Oceania: Within Oceania, compound flood events have been primarily observed in Australia and to a lesser degree New Zealand. In Australia, the highest frequency of compound flood events is along the northern coastlines (bearing the brunt of TCs (Claassen et al., 2023)) followed by the east and west coasts; all of which predominantly occur during TC season in austral summer. Examining dependence, these patterns are consistent for nearly all flood driver pair combinations, with strong positive correlation in all areas except the southern coast (particularly Victoria) for pluvial-coastal, fluvial-coastal, pluvial-fluvial, (Zheng et al., 2013; Ward et al., 2018; Wu et al., 2018; Couasnon et al., 2020; Ridder et al., 2020; Lai et al., 2021a; Lai et al., 2021b). In New Zealand, compound flood events from pluvial-coastal and fluvial-coastal drivers have been observed as being substantial but are not strongly correlated (Stephens and Wu, 2022). Compound flooding likely affects small Pacific Island Nations, however they have been scarcely studied. To-date, there are only two localized studies

(Chou, 1989; Habel et al., 2020) on co-occurring flood extremes for the entirety of Micronesia, Melanesia, and Polynesia. Habel et al. (2020) confirmed the occurrence of coastal-groundwater and pluvial-coastal flooding processes in Hawaii, and Chou (1989) quantified the frequency of compound flooding from tide and storm surge along Saipan in the Mariana Islands.

6.2) Dominant Drivers of Compound Flooding

While compound flood events involve a combination of drivers, often one of the components contributes more than the other(s). Understanding how drivers dominate the flooding process and how these change with space and time is essential to improving compound flood forecasting and risk assessment. Most compound flood events highlighted in the literature contain regions that are pluvial-, fluvial-, coastal-, groundwater-, or compound-dominated in nature. Only a handful of studies examine driver dominance at a global scale (Eilander et al., 2020; Lai et al., 2021b), but those that do reveal general patterns that also tend to be supported by more localized research. First, estuaries tend to have a mixture of dominant drivers. In a global assessment of 3,433 estuaries, Eilander et al. (2020) classified 19.7% as compound dominant, 69.2% as fluvial dominant, and 7.8% as coastal dominant. Next, coastal-only environments (i.e., coastal areas with little or no river interaction) have a much larger proportion of coastal-dominant compound floods due to the direct proximity of tide-surge processes and wave actions; and groundwater-dominated floods where sea level (and salinity differences) push the water table up. Excluding river processes, Lai et al. (2021b) deduced that coastal (storm surge) and pluvial flooding contributed 65% and 35% to the global change in annual compound floods, respectively. Finally, urban coastal regions are expected to have a greater number of pluvial-dominated compound floods.

Flood driver dominance can depend on topography and channel morphology (i.e., depth, width, size, shape, volume, slope, friction, and damping) (Eilander et al., 2020; Bermúdez et al., 2021; Tanim and Goharian, 2021; Familkhalili et al., 2022; Harrison et al., 2022), spatial extent (i.e., location within hydrological network and distance to the coast) (Moftakhari et al., 2019; Bermúdez et al., 2021; Del-Rosal-Salido et al., 2021; Huang et al., 2021; Ye et al., 2021; Gori and Lin, 2022;

Juárez et al., 2022; Sampurno et al., 2022b; Sebastian, 2022; Zhang and Chen, 2022), elevation (Huang et al., 2021; Liang and Zhou, 2022), ground-surface connectivity (Jane et al., 2020), and meteorologic modulator characteristics (i.e., storm event timing and intensity) (Tanim and Goharian, 2021; Gori and Lin, 2022). Pluvial flooding is the least frequently reported dominating driver, and primarily only occurs in areas disconnected from the river network with no fluvial inundation (Apel et al., 2016; Ye et al., 2021; Gori and Lin, 2022) or at higher elevations (Berghuijs et al., 2019; Huang et al., 2021). Pluvial-dominated flooding is also prevalent in urban zones when the capacity of drainage systems is exceeded (Shi et al., 2022), areas with high antecedent soil moisture (e.g., Europe as a whole) and/or snowmelt (e.g., Scandinavia and northeast Europe) (Berghuijs et al., 2019), and regions with strong connectivity of surface and groundwater networks (Jane et al., 2020). Fluvial processes dominate inland flooding in watershed catchments from channelized freshwater in dynamic hydrological networks. Flooding can also be fluvial-dominant in coastal regions fed by steep mountainous rivers that respond quickly to rainfall and snowmelt (e.g., Zhejiang China (Liang and Zhou, 2022)). Within primarily coastally-influenced regions, driver dominance can be further broken down into surge-, wave-, and tide-dominated. Which of the components of extreme sea level is the principal driver varies on continental to regional scale depending on meteorological modulators and characteristics of landmasses.

In the case of mixed fluvial and coastal flooding in estuaries and deltas, identifying the dominant driver is more challenging as it varies based on location and channel geomorphology. River-sea interactions are highly dynamic, and the sensitivities of flood components can fluctuate greatly within a single estuary or delta (Hoitink and Jay, 2016; Harrison et al., 2022). Common methods of classifying regions of driver dominance usually involve using Flow Interaction Indices (Valle-Levinson et al., 2020; Juárez et al., 2022) and Compound Hazard Ratio Indices (Shen et al., 2019; Valle-Levinson et al., 2020; Jalili Pirani and Najafi, 2022b; Juárez et al., 2022). As expected, most researchers have found that the lower estuary is tide- or surge-dominated, the middle estuary transition zone may be considered compound-dominated, and the upper watershed region is discharge-dominated (Moftakhari et al., 2019; Bermúdez et al., 2021; Del-Rosal-Salido et al., 2021; Huang et al., 2021; Ye et al., 2021; Gori and Lin, 2022; Juárez et al., 2022; Qiu et al., 2022; Sampurno et al., 2022b; Sebastian, 2022; Zhang and Chen, 2022). General patterns of driver dominance are different across estuaries depending on the properties of watershed drainage basins (i.e., topography and morphology) and the behavior of storm events (i.e., path, orientation, intensity, duration, and time lag between drivers). Numerous studies map out regions dominated by each of the different flood drivers (Chen et al., 2010; De Bruijn et al., 2014; Gori et al., 2020b; Bilskie et al., 2021; Del-Rosal-Salido et al., 2021; Maymandi et al., 2022), often zoned as coastal, hydrological (fluvial and/or pluvial), or transition/compound (combined drivers determine the max water levels) based on numerical model simulations using different scenarios. The exact scenario definitions however often vary between studies making it difficult to compare results. Compound-dominant floods usually have greater surge extremes and quicker discharge due in part to flatter topography (Eilander et al., 2022b). In estuaries, channel convergence has been shown to influence tidal propagation such that strongly dissipative and convergent estuaries tend to be flood-tide dominant while weakly dissipative estuaries are ebb-tide dominated (Lanzoni and Seminara, 1998). Large rivers are usually fluvial-dominant, while smaller and less connected rivers are more likely to be influenced by precipitation at the coast (Bevacqua et al., 2020a). Similarly, increasing channel depth reduces the impact of fluvial processes while amplifying the effect of coastal drivers on total water level (Familkhalili et al., 2022). Therefore, channel deepening pushes the compound-dominated region further upstream and shortens the length of fluvial-dominated estuary. Flood dominance can also be significantly affected by the magnitude and severity of storm events such that a single location can be dominated by different drivers from different return period storms. Gori et al. (2022) observed surge-dominated flooding at the coast for low return period events, but compound-dominated flooding for high (100-year) return periods.

Fewer studies have examined the role of timing on flood driver dominance. In the case of TC/ETC events, there is a time lag such that it can be hypothesized that coastal areas are first inundated by storm-tide followed by river discharge from upstream rainfall. Thus, at the beginning of storm events flooding is likely coastal (and/or pluvial) dominated and later switches to being compound dominated and then finally fluvial (and/or pluvial) dominated. For instance, the 1991 cyclone that hit Chittagong Bangladesh had a 5-hour difference between peak surge and peak rainfall (Tanim and Goharian, 2021). As a result, the flooding began as coastal-dominated and then shifted towards being pluvial-dominated. The importance of timing may also fluctuate depending on the size of the water bodies in question. Dykstra and Dzwonkowski (2021) found that slowing of river propagation in larger watersheds (>5000 km^2) led to a greater time lag between storm surge and river discharge, indicating a greater risk of fluvial-coastal compounding in smaller watersheds where discharge travels downstream faster. Likewise, differences observed in the UK's Humber and Dyfi estuaries explain why maximum flood depth from fluvial-coastal compounding is less sensitive to timing in the case of a larger estuary (Humber) subject to slow river discharge, compared with short intense discharge in a smaller estuary (Dyfi) (Harrison et al., 2022).

6.3) Urban and Coastal Infrastructure

Urban areas are identified in the literature database to be especially vulnerable to compound flooding, as the built environment can exacerbate the effects of flooding, and the concentration of people and infrastructure can lead to significant losses. In the coastal environment, hazard modelling and risk assessment practices regularly consider the influence of flood defence structure (i.e., barriers, sea walls, groynes, breakwaters), however other aspects of human activity (e.g., coastal and floodplain development and modification, land use/land cover change) and urban infrastructure (e.g., sewer waste drainage systems, water management reservoirs) receive less attention. Furthermore, existing urban infrastructure planning and risk assessment practices generally do not consider the ramifications of compounding flood drivers and thus underperform or have a greater chance of failure from compound flooding (Archetti et al., 2011; Jasim et al., 2020; Najafi et al., 2021). For instance, in Jasim et al. (2020), coastal earthen levees were simulated to experience 8.7% and 18.6% reductions in the factor of safety for 2-year and 50-year recurrence intervals under compound pluvial-fluvial flood conditions compared to fluvial-only flooding. Similarly, Khanam et al. (2021) found that FEMA maps significantly underestimate risk at several power grid substations in coastal Connecticut by not accounting for compound flood interactions This section will discuss how compound floods influence the performance of urban and coastal infrastructure, and how infrastructure in these settings can either amplify or reduce the risks and impacts of compound floods.

It is well established that the risks and impacts of compound flooding can be elevated in coastal and urban settings. Private property and public utilities developed within floodplains and along shorelines are more likely to be exposed to multiple coinciding flood mechanisms. Over the past century, changes in land use/land cover have made the urban environment increasingly susceptible to flooding. Urban areas experience increased precipitation as unstable warm city air masses rise (i.e., urban heat island effect) and then cool, forming rainclouds. This rain falls onto impervious surfaces (i.e., asphalt and concrete) and compacted soils (from construction and agriculture) which prevent surface water from seeping into the ground and percolating down into underlying aquifers (Shahapure et al., 2010). Instead, water finds its way into river channels and urban drainage networks which act as highways and rapidly deliver vast volumes of water to the coast. During TC events, rainfall and river discharge are more likely to temporally overlap with coastal storm surge due to the heightened mobility of water within the urban environment. It is this combination of urban land cover and storm-sewer drainage infrastructure that plays a substantial part in amplifying the impacts of urban coastal compound floods (Meyers et al., 2021). It has been well demonstrated that elevated water levels at the coast from storm surge can significantly reduce the rates of urban drainage resulting in more severe flooding (Bunya et al., 2010; Zellou and Rahali, 2019; Shi et al., 2022). Accumulated surface runoff in cities is meant to flow into rivers and ultimately the ocean, but high tides or waves can either block or force this water back inland. It has also been shown that poorly maintained and leaking stormwater drainage systems can cause compound pluvial-groundwater and fluvial-groundwater flooding where seawater travels inland via drainage systems (known as ‘drainage backflow’ and ‘seawater intrusion’) and flood areas near (and sometimes far from) the coast (Habel et al., 2020; Qiang et al., 2021; Sangsefidi et al., 2022; Sebastian, 2022). Furthermore, human activity including coastal and riverine modifications (i.e., dredging and straightening) (Muñoz et al., 2022b) in favor of water utilities (e.g., hydroelectric) and transportation (e.g., marine shipping) also may increase the risks and impacts of compound flooding as decreased channel friction causes heightened propagation. Changing the morphology of coastal channels as often seen in urban ports, can amplify fluvial-coastal and pluvial-coastal compound flooding due to reduced dissipation of energy and thus increased extreme peaks. Lastly, urban and coastal environments also pose the rare but catastrophic potential of damming/dam failure related compound flooding. For example, Typhoon Rusa led to compound coastal-pluvial-damming/dam failure flooding in the urban city of Gangneung (Kim and Sanders, 2016). The failure of two upstream dams in combination with heavy rainfall and storm surge caused extensive damage to major infrastructure and affected hundreds of households. A very similar scenario occurred in Qianbujing Creek, Shanghai during Typhon Fitow, involving compound heavy rainfall, river discharge, and levee-break flooding (Yang et al., 2021).

Urban infrastructure can also reduce the risks and impacts of compound flooding if designed to be resilient and forward-looking. Management and policy decisions regarding urban infrastructure investment, maintenance, and outreach can play a large role in shaping compound event risk through the lens of population exposure and vulnerability (Raymond et al., 2020). Well-maintained and operated coastal urban infrastructure from flood defence (e.g., storm surge barriers, sea walls, levees, breakwaters, and groynes) to flow management systems (e.g., dams, stormwater sewers, sump pumps, dry wells) can act to minimize compound flood risk when the dependence of multiple drivers is adequately considered. Furthermore, sustainable urban drainage systems (e.g., swales, infiltration trenches, retention basins, green roofs, and permeable paving) (EAA, 2017) can reduce the likelihood of compound flooding as they can create a time lag between peak pluvial, groundwater, and coastal processes. Lastly, natural flood management practices (e.g., wetland/floodplain/lake restoration, riverbed material re-naturalisation, river re-meandering) (EAA, 2017), can also serve to spread out the duration and reduce the acute impact of compounding involving fluvial and coastal drivers, advancing the resiliency of urban and coastal environments.

6.4) Compound Flooding and Changing Climate

Many studies in the database stress that future compound flood risk is likely to increase from changes in the variability, intensity, frequency, phasing, and seasonality of sea level, precipitation, river discharge, and temperature driven by climate change (Zscheischler et al., 2020; Harrison et al., 2022). Under a changing climate the interrelationships and dependence between variables contributing to compound events are likely to change; giving rise to greater uncertainty. A projected warmer atmosphere will bring more frequent and intense storms and rainfall in many parts of the world (Bevacqua et al., 2019; Bevacqua et al., 2020b; Wasko et al., 2021; Zhang et al., 2022), with some estimating a 25% global increase in compound floods by 2100 (RCP8.5) (Bevacqua et al., 2020b). For example, the UK is expected to see increased clustering and intensity of storms (particularly in the winter) such as those seen in 2013/14 (Harrison et al., 2022; Jenkins et al., 2023). The relative influence of rainfall on total flooding is increasing due to the warming climate (Swain et al., 2020; Burn and Whitfield, 2023), and long-term increases in the frequency of compound coastal river flooding from intensifying precipitation has already been observed throughout the past century (Dykstra and Dzwonkowski, 2021). This is particularly the case for the high latitudes (Bevacqua et al., 2020b) including the US East and Gulf Coasts as well as northern Europe, which face increasing risk from the joint occurrence of rainfall and storm surge (Wahl et al., 2015; Bevacqua et al., 2019; Ghanbari et al., 2021; Gori et al., 2022), having already seen a rise in the number of annual compound events by 1-4 per decade (Lai et al., 2021b). Trends of raising frequency of concurrent precipitation and storm-tide have additionally been observed at other coasts globally, including Russia, Japan, Korea, China, Bangladesh, northwest South America, southern Chile, northern Australia, and New Zealand (Bevacqua et al., 2020b; Lai et al., 2021b). SLR is additionally anticipated to substantially amplify the likelihood of compound flooding at the coast (Wahl et al., 2015; Ganguli et al., 2020; Bermúdez et al., 2021; Ghanbari et al., 2021; Harrison et al., 2022), with global mean sea level projected to increase 0.61-1.10m (RCP8.5) by 2100 (Church et al., 2013). This is already drastically affecting island nations in southeast Asia and the Pacific that are vulnerable to compound coastal flooding involving storm events (Kuleshov et al., 2014; Hsiao et al., 2021; Leijnse et al., 2021). Global coastal regions have become increasingly sensitive to inundation from combined influences of SLR, surge, tide, and waves (Dahl et al., 2017; Idier et al., 2019; Oppenheimer et al., 2019; Sheng et al., 2022). This is evident in coastal south and southeast Asia where climate-induced storminess and high-tide extremes increasingly drive more extreme sea levels, in addition to sea level rise (Xu et al., 2014; Wood et al., 2024). Tidal amplitude is also changing globally (Pickering et al., 2017), and in some regions is driving a greater proportion of both extreme and nuisance flooding (Pickering et al., 2017; Sweet et al., 2018; Haigh et al., 2020; Shen et al., 2022). Total coastal flooding globally is estimated to be 68% caused by storm and tide with 32% attributed to relative SLR (RCP8.5) (Kirezci et al., 2020). Furthermore, non-stationarity in compound flooding has been well documented, with climate-induced shifts in the seasonal timing of peak flood driver occurrence. Analysis of historical long-term flood driver trends throughout Europe has revealed single week to full month shifts in mean flood occurrence date. Rainfall and river floods have shifted earlier along the Atlantic, in the Baltics, and western Italy; and later in eastern Europe, southern France and Spain, and along the North Sea (Blöschl et al., 2017; Tramblay et al., 2023). In the case of mixed rainfall-snowmelt coastal catchments in the Nordic countries, Vormoor et al. (2015) observed a shift forward in the flood regime from spring-summer to fall-winter as rainfall replaces snowmelt as the dominant driver due to raising temperatures.

While compound flood frequency is generally thought to increase globally, it is critical to understand that compound flooding may also decrease in some select regions due to changing local hydrometeorological and climatic forcings. In the case of the Upper Mahanadi River basin, Khatun et al. (2022) projected lower compound flood hazards under future climate scenarios involving preconditioned rainfall and river discharge. Bevacqua et al. (2020b) project that the joint probability of rainfall and storm surge will decrease in portions of the subtropics; noting the most significant shift in the Mediterranean and the Strait of Gibraltar (Bevacqua et al., 2019) and potentially attributing changes to reduced regional extreme sea levels. Lai et al. (2021b) have similar findings, observing a decrease in annual compound flood events in the southern Mediterranean and Japan. In contrast to that of Bevacqua et al. (2020b), Ganguli et al. (2020) project a lower joint probability of storm surge and river discharge extremes in northwest Europe, attributing changes to weakening driver dependence. The conflicting findings of these two studies highlight the limitations (e.g. sensitivity, internal variability, and uncertainty) of using a small ensemble of climate models for projecting future compound flood joint probability. Lastly, many of these trends towards decreased compounding are the result of changes in sea level pressure, coastal wind, precipitable water content, and convection patterns that either reduce the magnitude of individual flood drivers (often precipitation in tropics) or the dependence between drivers.

In summary, across the studies reviewed, climate change is shown to have a profound impact on the frequency, severity, and timing of compound coastal flooding events (Sebastian, 2022). Furthermore, extreme total sea levels from the combination of SLR, surge, waves, tidal cycles, and changes in the frequency and intensity of storms are “very likely” to increase over the next century in many regions of the world (Idier et al., 2019; Oppenheimer et al., 2019).

6.5) Research Approaches

As highlighted in Section 5.4, we identified two main categories of approaches that have been used to assess compound flooding, namely, (1) physical (process-based) numerical modelling; (2) and/or statistical modelling/analysis. In both approach classes we observed a diversity of methods, similar to the findings of Tilloy et al. (2019). Below, we discuss the use of computational numerical methods for compound flood modelling (Section 6.5.1), then provide an overview of the statistical and data science-based techniques for analysing compound flooding (Section 6.5.2), and finally reflect on the benefits of hybrid (combined numerical-statistical) approaches (Section 6.5.3).

6.5.1) Numerical Modelling

Compound flood events are often examined by numerically modelling the physics-based interactions of their processes and mechanisms. Through the simulation of historical and synthetic compound flood events, researchers can develop a better understanding of present and future inundation magnitude and extent. Given the highly complex nature of compound flooding, numerical modelling often requires a combination of hydrological, hydrodynamic, and atmospheric/climate models to represent all Earth system components contributing to compound flooding. A range of different numerical models are used in the literature, as we briefly discuss here. Further information on the hydrological, hydrodynamic, and atmospheric models, frameworks, systems, and toolsets used in the reviewed studies is provided in Table A2.

Hydrological models are used to simulate the movement, storage, and transformation of water within the hydrological cycle. These include land-atmosphere water exchange (precipitation and evapotranspiration), the flow of water through the landscape (streamflow and rainfall-runoff), and the infiltration of water into the ground (groundwater recharge). Hydrodynamic models use a series of governing equations (e.g. shallow-water equations) to simulate the flow of water in rivers, oceans, estuaries, and coastal areas. Coastal hydrodynamic models replicate the propagation and advection of water based on a combination of tide, surge, and waves. In the realm of compound flooding, hydrodynamic models are vital for simulating the effects of complex river-ocean interactions, storm surge, lake seiche, and flood infrastructure. Atmospheric models simulate various atmospheric processes based on primitive dynamic equations explaining radiation, convection, heat flux, gas exchange, kinematics of air masses, the behavior of water vapor (precipitation and clouds), and land/ocean-atmosphere interactions. In compound flood research, numerical atmospheric modelling is generally used to simulate synthetic or historical storm events (TCs/ETCs) and to generate meteorological inputs (e.g., precipitation, atmospheric pressure, and wind velocity) that force hydrological and hydrodynamic models.

Compound flood modelling often involves the use of coupled or linked models. Individually, hydrological and hydrodynamic models are unable to capture the full dynamic interactions between inland and coastal processes (Ye et al., 2020). However, integrating the capabilities of both types of models can serve to better simulate the movement and transformation of water within a particular system as shortcomings of one model can be complemented by the strengths of another. Santiago-Collazo et al. (2019) define four techniques for linking different types of models: one-way coupled; two-way (or loosely) coupled; tightly-coupled; and fully-coupled. One-way coupling involves using the output of one model as the direct input for another model, such that data only transfers in one direction. Alternatively, two-way coupling describes a relationship in which the outputs of both models transfer information to each other iteratively, creating a two-way loop that influences the behavior of both. Tight coupling refers to the integration of two independent models into a single model framework at the source code level. A common example of tight-coupling is the ADCIRC-SWAN model. SWAN sends simulated waves to ADCIRC, and ADCIRC sends water levels and wind velocities back to SWAN. Lastly, full coupling is the complete integration of all model components such that physical processes are calculated simultaneously under the same framework using the same governing equations. We observed that most of the existing compound flood indentation modelling implements simple one-way or two-way coupling approaches (Santiago-Collazo et al., 2019; Xu et al., 2022). Fully coupled numerical models are rare in compound flood research, as most models only specialize in one or two earth systems (i.e., meteorology, climatology, hydrology, and oceanography).

6.5.2) Statistical Approaches and Dependence Analysis

Across the studies we have reviewed, a wide variety of statistical-based approaches have been employed to understand trends, patterns, and relationships using observed data, sometimes complemented by physically simulated data. This predominantly involves the use of statistical models as an indirect measure of compound flooding potential to better understand the dependence between different flood drivers and the likelihood of their joint occurrence.

Several broad statistical techniques are frequently used for compound flood research. Some of the most prominent methods include varying forms of spatial and temporal analysis, regression analysis, extreme value analysis, Bayesian probability, principal component analysis, index analysis, Markov chains, and machine learning (ML). Spatial and temporal analysis investigate correlations, covariance, trends, and patterns in where and when compound flood events occur. This can include identifying compound flood hotspots (Ganguli and Merz, 2019a; Ridder et al., 2020; Camus et al., 2021; Lai et al., 2021b; Camus et al., 2022) and temporal clustering (Haigh et al., 2016; Santos et al., 2017; Camus et al., 2021; Banfi and De Michele, 2022; Manoj J et al., 2022) or examining the underlying spatiotemporal preconditions and interactions of flood components (Camus et al., 2022; Manoj J et al., 2022). Regression analysis involves using statistical functions to identify relationships between independent and dependent flood variables by fitting data to linear and higher-order non-linear functions (Zhong et al., 2013; Orton et al., 2015; Van Den Hurk et al., 2015; Serafin et al., 2019; Bermúdez et al., 2021; Ghanbari et al., 2021; Lai et al., 2021b; Meyers et al., 2021; Mohammadi et al., 2021; Robins et al., 2021; Santos et al., 2021b; Zhang et al., 2021b; Jang and Chang, 2022; Sampurno et al., 2022a). Extreme value analysis examines the tail distribution or threshold exceedances of extreme flood variables to better understand joint-probability, uncertainty, and severity (Dixon and Tawn, 1994; Kew et al., 2013; Orton et al., 2016; Vitousek et al., 2017; Pasquier et al., 2019). Bayesian statistical approaches can iteratively recalculate the likelihood of an event based on new evidence. Bayesian frameworks are often used to update predictions about compound flood hazards based on new data and to understand the uncertainties associated with these hazards (Orton et al., 2015; Bass and Bedient, 2018; Couasnon et al., 2018; Bermúdez et al., 2021; Mohammadi et al., 2021; Steinschneider, 2021; Gori and Lin, 2022; Naseri and Hummel, 2022). Principal component analysis is a method of reducing the dimensionality of data by selecting the most important variables and combining them into a smaller volume of composite variables. In compound flood research this approach can be used to reduce the complexity of compound flood data to identify the key factors contributing to compound flood hazards (Camus et al., 2022). Index analysis is a method of data interpretation in which statistical indices simplify our understanding of the behavior of multiple variables, a practice commonly used for flood risk and impact analysis (Rueda et al., 2016; Valle-Levinson et al., 2020; Tanir et al., 2021; Huang, 2022; Jalili Pirani and Najafi, 2022b; Juárez et al., 2022; Khatun et al., 2022; Preisser et al., 2022; Tao et al., 2022). Compound flood research takes this further using various indices that also consider the synergy of multiple flood drivers (Tanir et al., 2021; Jalili Pirani and Najafi, 2022a, b; Juárez et al., 2022; Khatun et al., 2022; Preisser et al., 2022; Tao et al., 2022). Markov chains use records of past variable states to describe the probability of future states. With this approach, flood variable data such as rainfall and river levels can be fit to stochastic models to simulate the probability of joint extreme states. Additionally, Monte Carlo Markov Chain (MCMC) approaches involving stochastic sampling of variables are sometimes also applied in compound flood research (De Michele et al., 2020; Ganguli et al., 2020; Jalili Pirani and Najafi, 2022a; Jong-Levinger et al., 2022). Lastly, in recent years ML models involving varying neural network structures have been trained using compound flood datasets to predict flood extremes or map inundation extents (Karamouz et al., 2014; Bass and Bedient, 2018; Serafin et al., 2019; Muñoz et al., 2021; Santos et al., 2021b; Huang, 2022; Sampurno et al., 2022a).

Understanding the dependence of compound flood variables is crucial as it tells us about their joint exceedance probability (Ward et al., 2018; Xu et al., 2022). Failure to investigate driver dependence will lead to an underestimation of flood probabilities. Varying forms of the Joint Probability Method (JPM) (Myers, 1970; Ho and Myers, 1975; Pugh and Vassie, 1980), involving aspects of extreme value analysis, are commonly used to measure potential co-occurrence and dependence between compound flood drivers. Over time the analytical approaches have evolved, but generally involve three main steps for investigating dependence and frequency of cooccurring events. First, the flood variable event sets are sampled. The second step involves a simple calculation of varying correlation coefficients from the driver data. The third step consists of fitting a multivariate distribution function.

In preparation for the following steps, flood variables datasets are created by sampling events (according to varying compound scenarios, i.e., AND, OR, Kendall) via block-maxima or threshold-excess (peak-over-threshold, POT) methods. Block maxima sampling selects the maximum events within a given temporal block (annual, seasonal, daily), while the threshold-excess method selects events above a defined 'extreme' threshold value. Lucey and Gallien (2022) suggest that block maxima sampling has the potential to underestimate water levels for extreme events (in semi-arid climates), however both block maxima and threshold-excess approaches likely have limitations depending on their implementation. Next, the correlation coefficient step typically implements different types of rank correlation coefficients and tail coefficients. Correlation coefficients such as Kendall's tau τ and Spearman's ρ can reveal non-linear relationships between random variables based on their ordinal associations. Alternatively, the lower (λ_L) and upper (λ_U) tail coefficients help examine dependence between random variables at the extremes of their distributions. While random variables may appear to show no correlation at a standard significance level, the co-movement of their tails may reveal dependence relationships that only occur at the extremes. The joint probability distribution is then constructed from the sampled variable event datasets as the probability of all possible pairs across each input variable. The joint probability distribution thus defines the probability of two or more simultaneous events, where the variables are at least partially dependent, and thus influence each other's occurrence (Hawkes, 2008). Similarly, event coincidence analysis can be used to examine the joint occurrence of variables. This approach relies on variable time series (observed or modelled) and counts instances of coincidence, where two or more variables or events co-occur within a defined time window (Donges et al., 2016). Coincidence rate can then by calculated to assess the frequency of event coincidence over time.

In recent years, copulas have also been used to measure dependence, gaining considerable attention for their ability to simplify the analysis of highly stochastic multivariate processes. A total of 64 (23%) studies were observed using copula-based methods to assess dependence. Defined in Sklar's theorem (Sklar, 1959), a copula is a multivariate cumulative distribution made by joining or “coupling” the univariate marginal probability distributions of two or more individual variables. This can be done using several dependence structures, with common copula families being Elliptical and Archimedean. In addition to measuring dependence, copulas are used in compound flood research to assess the non-linear relationships and uncertainties between extreme flood variables (Salvadori and De Michele, 2004, 2007). By fitting copula functions to multivariate flood data, it is possible to understand the strength and nature of the dependence between these variables and to predict the likelihood of compound flood events. To date, the majority of compound flood research involves bivariate case studies. Nonetheless, several studies have implemented trivariate approaches to simultaneously analyse three partially dependent variables (Hawkes et al., 2002; Yang and Qian, 2019; Jalili Pirani and Najafi, 2020; Jane et al., 2020; Santos et al., 2021a; Jalili Pirani and Najafi, 2022b; Latif and Simonovic, 2022b, a; Ming et al., 2022; Zhang and Chen, 2022; Latif and Simonovic, 2023), and others have taken more complex procedures integrating copulas with MCMC (Sadegh et al., 2018; Moftakhari et al., 2019; De Michele et al., 2020; Ganguli et al., 2020) and Bayesian network (Couasnon et al., 2018; Moftakhari et al., 2019; Jalili Pirani and Najafi, 2022a; Naseri and Hummel, 2022) approaches. For further detail on copula-based multivariate flood analysis see Latif and Mustafa (2020).

6.5.3) Hybrid Modelling and Analysis Approaches

Research methodologies involving a combined numerical and statistical approach were observed in around one-third of the compound flood studies (Figure 6). In this review we use “hybrid model” to refer to this combined numerical (process-based) and statistical (data-driven) approach. We note that there is currently no standard meaning around the term “hybrid”, and thus our interpretation may conflict with the perspectives of others. Some use “hybrid” when considering the linking of multiple numerical modelling components or in the case of various ML statistical models. Others use this term in reference to model frameworks involving a combination of parametric and nonparametric components. Nonetheless, these hybrid approaches can complement each other or focus on multiple aspects of modelling in a way that would not be possible when using numerical or statistical approaches in isolation. For example, process-based numerical modelling of compound flood hazards may be ideal for physics-based inundation mapping and floodplain delineation, but can be very computationally expensive (this has pushed the development of more computationally efficient models such as SFINCS (Leijnse et al., 2021)). Conversely, simplified statistical models are less computationally expensive, but typically make general assumptions about input data that do not fully consider the physical processes at play. In contrast, hybrid numerical-statistical approaches offer the benefit of computationally efficient surrogate statistical modelling while still maintaining a realistic representation of the physical processes (Serafin et al., 2019). Additionally, numerical modelling can also be severely inhibited by historical data availability. Hydrodynamic modelling of astronomical tide and storm surge require atmospheric pressure and wind velocity forcing data, while past river level and rainfall data is dependent on the presence of in-situ tide and rain gauge monitors. In the event of absent of poor spatiotemporal coverage, numerical hydrodynamic models must rely on reanalysis datasets (i.e., assimilation of observations and numerical weather prediction models). Statistical approaches to compound flood analysis however can sometimes make do with limited data by interpolating or extrapolating extreme hazard probabilities and distributions. In the absence of historical data, one solution is to numerically simulate synthetic events that are physically capable of occurring, albeit not present in short-term observations (Serafin et al., 2019). For instance, Bloemendaal et al. (2020) demonstrate the synthetic resampling algorithm STORM’s ability to generate 10,000 years of TC activity based on 38 years of historical data from IBTrACS. Many hybrid approach compound flood studies statistically simulate storm events that drive physical hydrodynamic and hydrological models (Moftakhari et al., 2019; Serafin et al., 2019). Limitations of this approach center on the fact that statistically generated event sets and reanalysis data may under-represent extremes, exhibit inherent systematic modelling, and/or inadequately account for climate nonstationarity (Bengtsson et al., 2004; Easterling et al., 2016; Brönnimann et al., 2019).

6.6) Research Applications

As highlighted in Section 5.5, we identified that six main applications have been the focus of most compound flood studies in the database. Discussed in the following order, prominent case study applications include earth system processes (Section 6.6.1); risk assessment (Section 6.6.2); impact assessment (Section 6.6.3); forecasting (Section 6.6.4); planning and management (Section 6.6.5); and methodological advancement (Section 6.6.6). Note, that many of the compound flood studies fall into multiple application categories.

6.6.1) Earth System Processes

From the 279 literature database entries, 130 (47%) seek to better understand the processes, interactions, and behavior of earth systems associated with compound flooding. Research papers within the earth system processes application theme examine a variety of topics including the role of various dynamic Earth systems on compound flooding, the environmental and landscape characteristics influencing flood drivers, the relationships between and relative significance of flood drivers, and the spatiotemporal distributions and frequency of compound flood events. Many of the papers discussed in Sections 6.1, 6.2, and 6.5 fall within this application category.

Focusing on flood drivers relationships, there is a plethora of research examining aspects of spatiotemporal distribution, correlation, covariance, dominance, and dependence structures as demonstrated in the US (Serafin and Ruggiero, 2014; Nasr et al., 2021; Juárez et al., 2022; Maymandi et al., 2022), UK (Svensson and Jones, 2002, 2004; Haigh et al., 2016; Santos et al., 2017; Hendry et al., 2019), Europe (Klerk et al., 2015; Petroliagkis, 2018; Ganguli and Merz, 2019b; Camus et al., 2021), Australia (Zheng et al., 2013; Zheng et al., 2014; Wu et al., 2018; Wu and Leonard, 2019), Canada (Jalili Pirani and Najafi, 2020, 2022b), China (Qiu et al., 2022; Tao et al., 2022; Zhang and Chen, 2022), South Africa (Kupfer et al., 2022), India (Manoj J et al., 2022), Indonesia (Sampurno et al., 2022b), New Zealand (Stephens and Wu, 2022), and globally (Ward et al., 2018; Couasnon et al., 2020; Ridder et al., 2020; Lai et al., 2021a). Many have simulated or projected how climate change (e.g., SLR and storm intensification) are expected to affect the future compounding interactions of flood drivers (Wahl et al., 2015; Bevacqua et al., 2019; Pasquier et al., 2019; Ganguli et al., 2020; Bermúdez et al., 2021; Ghanbari et al., 2021).

There is also notable insight into the large-scale meteorological and climatological modulators and underlying earth systems influencing the nature of compound flooding and the behavior of flood drivers. For instance, Camus et al. (2022), Hendry et al. (2019), and Rueda et al. (2016) identify the meteorological conditions associated with the compound occurrence of extreme flood drivers in the North Atlantic, the UK, and Spain respectively. Gori et al. (2020a) and Gori et al. (2020b) determine the type of TC events likely to cause compound pluvial-coastal flooding in North Carolina. Stephens and Wu (2022) identify the weather types corresponding with both univariate and coincident pluvial, fluvial, and coastal extremes in New Zealand. Furthermore, Wu and Leonard (2019) demonstrate how ENSO climate forcings impact the dependence between rainfall and storm surge extremes.

Other common focuses of earth system processes themed literature include characterizing the physical mechanics and environmental properties that shape how flood drivers interact. Several papers including Vongvisessomjai and Rojanakamthorn (1989), Poulos et al. (2022), and Pietrafesa et al. (2019) evaluate the timing and mechanisms behind downstream blocking and dampening that often explain fluvial-coastal flooding. Similarly, Maymandi et al. (2022) measure the timing, extent, and intensity of storm surge, river discharge, and rainfall components to understand their relative importance. Likewise, Tanim and Goharian (2021) observe how changes in tidal phase alter the depth and duration of urban compound pluvial-coastal flooding. Harrison et al. (2022) and Helaire et al. (2020) measure how estuary characteristics (e.g., shape, size, width) influence fluvial-coastal dynamics. Wolf (2009) considers how wind stress, bottom friction, depth, bathymetry, and ocean current refraction change co-occurring surge and wave extremes (coastal-coastal). Torres et al. (2015) and Gori et al. (2020b) examine the influence of hurricane landfall location, angle of approach, and forward speed on compound rainfall-runoff and storm surge flooding (pluvial-coastal). Tao et al. (2022) explore compound fluvial-pluvial flood scenarios involving upstream and downstream water levels, and how intensity, timing, duration, and dependence change based on synoptic and topographic conditions.

Lastly, while the occurrence of compound flooding is well recognized in coastal, estuarine, and delta environments, we note that emerging research has enhanced the understanding of compound flood processes in the context of coastal lake environments (Saharia et al., 2021; Steinschneider, 2021; Banfi and De Michele, 2022; Jalili Pirani and Najafi, 2022b). For example, Banfi and De Michele (2022) determine that flooding of Italy's Lake Como is primarily (70%) from temporal compounding of rainfall (pluvial-pluvial). In Lake Erie, Saharia et al. (2021) analyses compound flooding involving river flow and lake seiche (fluvial-coastal), showing for the first time how seiches can combine with hydrological processes to exacerbate flooding. Finally, along Lake Ontario, Steinschneider (2021) quantified the compounding nature and variability of storm surge and total water level (coastal-coastal).

6.6.2) Risk Assessment

The overarching goal of most compound flood research is to better understand risk, hence why 129 (46%) studies involve aspects of risk assessment. As defined by the UNDRR (2016), risk assessment is an approach for determining the state of risk posed by a potential hazard taking into account conditions of exposure and vulnerability. Risk assessment inherently plays a key role in several of the reviews' other research application categories including hazard planning and management as well as impact assessment.

As the field of compound event sciences advances, it has become increasingly clear that conventional univariate analysis cannot accurately capture the synergistic and non-linear risk of compound processes (Kappes et al., 2010; Leonard et al., 2014; Eshrati et al., 2015; Zscheischler and Seneviratne, 2017; Sadegh et al., 2018; Zscheischler et al., 2018; Ridder et al., 2020). A plethora of studies have concluded that traditional hazard analysis, in which flood variable dependence and synergy are not considered, underestimates the risk of compound extremes (Bevacqua et al., 2017; Bilskie and Hagen, 2018; Kumbier et al., 2018; Hendry et al., 2019; Huang et al., 2021; Eilander et al., 2022b). Jang and Chang (2022) determine that by not considering the multivariate nature of pluvial-coastal flooding, Taiwan's flood risk would be severely misestimated causing incorrect warning alarms and inadequate protection. Khalil et al. (2022) assert that failing to consider the interactions of multiple flood drivers would reduce flood levels by 0.62m and 0.12m in Jidalee and Brisbane. Similarly, Santos et al. (2021a) measured 15-35cm higher water levels for 1% annual exceedance probability events when considering dependence for trivariate fluvial-pluvial-coastal flooding in Sabine Lake, Texas.

There is a diversity of topics within the risk-themed compound flood literature, but many papers involve simple regional case studies or framework proposals (Najafi et al., 2021; Ming et al., 2022; Naseri and Hummel, 2022; Peña et al., 2022). Čepienė et al. (2022) examine the risk associated with combined fluvial-coastal flooding and how it will change with SLR at the port city of Klaipėda. Bischiniotis et al. (2018) assess the influence of antecedent soil moisture on flood risk in sub-Saharan Africa, showing that precipitation alone cannot explain flood occurrence. Along the coasts of Mozambique, Eilander et al. (2022a) demonstrate a globally applicable compound flood risk framework and Van Berchum et al. (2020) present the novel Flood Risk Reduction Evaluation and Screening (FLORES) model. Bass and Bedient (2018) create joint pluvial-coastal flooding probabilistic risk models built upon TC risk products in Texas. Lastly, a few studies examine the risk of Potential Loss of Life (PLL) such as De Bruijn et al. (2014) who present a Monte Carlo-based analysis framework for fluvial-coastal interactions in the Rhine-Meuse delta.

6.6.3) Impact Assessment

Impact assessment is the least common compound flood application with only 11 (4%) relevant studies. This may be because flood impact assessments have historically only been designed to address a single type of flooding at a time (Láng-Ritter et al., 2022). Additionally, flood loss modelling has largely targeted riverine floods, with less attention given to pluvial, coastal, or groundwater drivers. This is slowly changing, and in recent years a small portion of research has been dedicated to analysing the impacts of compound flood events (Habel et al., 2020; Tanir et al., 2021; Láng-Ritter et al., 2022; Preisser et al., 2022). Impact assessment differs from risk assessment in that it looks at the realized or impending outcomes of flood events rather than simply the event likelihood as a product of exposure and vulnerability. This involves identifying and analysing the physical (e.g., building and infrastructure damage), social (e.g., loss of essential services, household displacement, and community cohesion), and economic (e.g., loss of income, damage to business and industry, and disruption of transportation and supply chain) impacts of flooding.

Physical parameters for quantifying the empirical impact of flooding in an affected area can include water depth, flow velocity, inundation duration, water quality (contamination), land use/land cover change, and infrastructure damage. For example, Habel et al. (2020) look at the influence of compound floods and SLR on urban infrastructure and identify the roadways, drainage inlets, and cesspools that would fail under compound extreme conditions.

Social and economic flood impacts are routinely measured using multifaceted indices and damage models. Preisser et al. (2022) and Tanir et al. (2021) assess the impacts of compound flooding with SVI (Social Vulnerability Index; 42 variables) and SOVI (Socio-Economic Vulnerability Index; 41 variables) respectively. Karamouz et al. (2017) apply a flood damage estimator (FDE) model to quantify pluvial-coastal flood damages to buildings structures in New York City. Similarly, Ming et al. (2022) calculate the average annual loss in value of residential buildings in the Thames River catchment from compound high river flow, heavy rainfall, and extreme surge.

6.6.4) Forecasting

A total of compound flood studies in the database focus on flood forecasting. Flood forecasts are valuable emergency management tools that provide information on the location, timing, magnitude, and potential impact of impending flood scenarios (Merz et al., 2020). Together with monitoring and prediction, forecasts guide time-sensitive early warning systems and disaster reduction strategies to help communities prepare for and respond to flooding. As compound event-based perspectives gain traction, there has been emerging development of flood forecast models that consider the compound interaction of multiple drivers.

Several studies demonstrate the capabilities of integrated near-real-time observation-based hydrological river and hydrodynamic coastal flood models forced by already established meteorological forecasting systems (Stamey et al., 2007; Mashriqui et al., 2010; Park et al., 2011; Blanton et al., 2012; Dresback et al., 2013; Mashriqui et al., 2014; Blanton et al., 2018; Tehranirad et al., 2020; Cifelli et al., 2021). For instance, the fluvial-coastal flood forecasting system Hydro-CoSMoS detailed in Tehranirad et al. (2020) can predict tidal river interactions in San Francisco Bay. Over the Korean peninsula, Park et al. (2011) design a model for real-time water level forecasting of pluvial-coastal inundation such as seen during Typhon Maemi.

Much of the existing compound flood forecasting research has focused on advances in the development of monitoring and early warning systems for the US East Coast and Gulf of Mexico. Blanton et al. (2012) feature development of the North Carolina Forecasting System (NCFS) which predicts fluvial-pluvial-coastal flood variables. Van Cooten et al. (2011) showcase the Coastal and Inland Flooding Observation and Warning (CI-FLOW) Project's 7-day total water levels forecasts and potential for near-real-time fluvial-pluvial-coastal flood prediction. Dresback et al. (2013) develop the coupled hydrological-hydrodynamic model ASGS-STORM for forecasting joint fluvial-coastal inundation. Multiple studies also concentrate on flood forecasting in the Chesapeake Bay and the tidally-influenced Potomac River. Stamey et al. (2007) introduce the Chesapeake Bay Inundation Prediction System (CIPS), a prototype operational flood forecasting system for TC/ETC storm-induced fluvial-coastal flooding. This is followed by Mashriqui et al. (2010) and Mashriqui et al. (2014) who build a River-Estuary-Ocean (REO) forecast system to fill gaps in existing operational models.

Accurate forecast products are crucial to effective emergency management practices and reliable early warning systems. Ensemble modelling has been implemented in two compound forecasting studies as a means of minimizing uncertainty. Blanton et al. (2018) develop a hurricane ensemble hazard prediction framework and demonstrate the ability to forecast pluvial-coastal flooding with a 7-day lead simulation of Hurricane Isabel. Similarly, Saleh et al. (2017) showcase a 4-

day advance operational ensemble forecasting framework for fluvial-coastal flooding in Newark Bay during Hurricanes Irene and Sandy.

A small number of studies have also investigated the use-case of ML for forecasting compound flooding (Bass and Bedient, 2018; Huang, 2022; Sampurno et al., 2022a). For instance, Sampurno et al. (2022a) use a combined hydrodynamic and ML approach to forecast fluvial-pluvial-coastal flooding in Indonesia’s Kapuas River delta. Bass and Bedient (2018) take peak inundation levels from a coupled hydrological-hydrodynamic model results to train an Artificial Neural Network (ANN) and Kriging ML model for rapid forecasting of TC-driven pluvial-coastal extremes in Houston, Texas as a result of Hurricanes Allison and Ike. Finally, Huang (2022) constructs a Recurrent Neural Network (RNN) model that considers downstream geomorphological and hydrological characteristics to predict joint pluvial-coastal flooding in Taiwan.

6.6.5) Planning and Management

Within the literature database there are 28 (10%) papers that focus on different aspects of flood management and planning from emergency response to risk mitigation strategies. The UNDRR (2016) defines disaster management as the organization, planning, and application of measures for disaster response and recovery. Subsequently, disaster risk management is described as the use of disaster risk reduction strategies and policies to prevent, reduce, and manage risk (UNDRR, 2016). Flood management strategies might involve identifying areas for prioritized flood protection and building risk reduction structures such as building levees, dykes, barriers, and sea walls; or enacting changes in land use planning and zoning policy to minimize habitation and activity in floodplains.

Flood defence and water management structures have long been in use; however these features have predominantly been designed for responding to a single flood driver (e.g., storm surge) (Sebastian, 2022). Several studies examine the effectiveness of flood defence structures protecting against compound events. Christian et al. (2015) investigate the feasibility of a proposed storm surge barrier for mitigating pluvial-coastal flooding in the Houston Shipping Channel. Findings on the magnitude of reductions in surface height and floodplain area help guide project development decision-making by coastal and port authorities. Del-Rosal-Salido et al. (2021) develop management maps to support decision-making and long-term climate and SLR adaptation planning in Spain’s Guadalete estuary, identifying sites for potential flood barriers.

During extreme flood events, unpredictable impacts on utility and transportation infrastructure can exacerbate loss. Thus, another key component of flood management is flexible emergency response planning. Several articles address these elements of response planning and identify evacuation areas, routes, and emergency shelters in the event of compound flooding. In their analysis of urban infrastructure failure from compound flooding in Hawaii, Habel et al. (2020) locate road networks and urban spaces that are likely to be impassable and estimate the effects of traffic on resident evacuation. In the event of a typhoon landfall in the Korean peninsula, Park et al. (2011) design an early warning system for pluvial-coastal flooding that supports decision-making and response from local officials by identifying areas to evacuate. Blanton et al. (2018) also address emergency planning, developing a hurricane-driven inundation evacuation model that dynamically accounts for interactions of compound drivers.

Effective communication and outreach are additional critical components of flood hazard planning and mitigation. This includes educating the public about the types and considerations of flooding, collaborating with hazard managers and policy makers to address challenges in flood management, and timely dissemination of information on flood risk, evacuation routes, and emergency shelters. In a unique narrative paper, Curtis et al. (2022) interview emergency managers and planners on compound flood risk perceptions and challenges in North Carolina, revealing inadequacies in communication mediums and the ability to convey compound flood severity to the public. Similarly, hazard expert interviews in Modrakowski et al. (2022) center on the use of precautionary risk management strategies in the Netherlands, and examine how the perception of compound flood events in part shapes the flood management practices of local authorities. Interestingly, the two studies produce different findings for individual flood drivers; highlighting the regional differences in flood mechanisms. Curtis et al. (2022) recorded a greater perception of risk from fluvial and coastal dominant flooding as opposed to pluvial inundation. Conversely, Modrakowski et al. (2022) found that pluvial flooding (specifically heavy rainfall from cloudbursts) had a larger perceived risk, being equal if not greater than fluvial and coastal. Societal intuitions, beliefs, and attitudes surrounding hazards are not often considered, yet can provide substantial value for shaping the strategies and practices for more effective emergency response and risk reduction.

6.6.6) Methodological Advancement

The third most common application category is methodological advancement with 80 (29%) of the 279 studies aimed at testing and developing methodologies for research on compound floods. Methodological advancement is a broad application category, but most often describes research studies that investigate either new setups and frameworks for running numerical model simulations, or novel statistical modelling and analysis techniques for quantifying the likelihood of compounding extremes or behavior of interacting drivers. Papers classified as methodological advancement seek to better understand and showcase the feasibility, development, and/or performance of compound flood research methods. Here forward see Table A2 for full model names and descriptions.

In relation to advancements in numerical-based methodologies, many papers explicitly state their primary research objective is the development of a compound flood modelling system itself, such as Chen and Liu (2014) and Lee et al. (2019), who test whether their respective SELFE and HEC-HMS + Delft3D-FLOW model frameworks can sufficiently replicate the fluvial-coastal flood conditions observed during historical storm events. Bates et al. (2021) showcase a sophisticated 30m resolution large-scale LISFLOOD-FP model of the contiguous US that incorporates pluvial, fluvial, and coastal processes under the same methodological framework. Numerous papers focus on assessing the performance of specific computational software applications for simulating compound flooding. These primarily seek to provide insight for future development and use case applications. For instance, Bush et al. (2022) examine the benefits and drawbacks between ADCIRC and linked ADCIRC + HEC-RAS simulations of fluvial-coastal flooding. Bilskie et al. (2021) demonstrate a new approach for delineating coastal floodplains and simulating water levels using ADCIRCs “rain-on-mesh” modules forced by antecedent rainfall, TC-driven rainfall, and storm surge. Ye et al. (2020) use SCHISM to develop a 3D model that incorporates the baroclinic effects of storm surge and compare its performance against 3D barotropic and 2D model alternatives. Numerous studies incorporate sensitivity assessments, experimenting with model parameters and settings, and examining how they influence performance and uncertainty (Mcinnes et al., 2002; Brown et al., 2007; Orton et al., 2012; Olbert et al., 2017; Silva-Araya et al., 2018; Leijnse et al., 2021; Khalil et al., 2022; Lyddon et al., 2022). For example, Khalil et al. (2022) investigate how model mesh resolution affects flood discharge rates, revealing that finer meshes best replicate peak flows. Some studies introduce newly developed numerical models, such as Olbert et al. (2017), who present the first instance of a dynamically linked and nested POM + MSN_Flood framework for fluvial-pluvial-coastal flooding. Others focus on the computational efficiency of compound flood frameworks, such as Leijnse et al. (2021) who assess the reduced-physical solver SFINCS’s ability to accurately simulate fluvial-pluvial-coastal interactions with less computational resources.

Many of the literature database studies showcase innovations in statistical approaches to compound flood research. Sampurno et al. (2022a) assess the operational viability and performance of three ML algorithms for a compound flood forecasting system. Similarly, Muñoz et al. (2021) examine the capability of ML and data fusion-based approaches for post-event mapping of compound floods from satellite imagery. Muñoz et al. (2022a) demonstrate techniques for employing data assimilation to reduce uncertainty in compound flood modelling. Wu et al. (2021) experiment with three methods of compound flood frequency analysis and discuss the advantages and disadvantages of each approach. Phillips et al. (2022) examine combinations of varying copula structures and statistical fitting frameworks to further approaches for measuring driver dependence. Thompson and Frazier (2014) test out different means of deterministic and probabilistic modelling for quantifying compound flood risk. Lastly, some studies expand on existing methodologies to overcome known limitations, such as Gouldby et al. (2017) who develop a method of full multivariate probability analysis that overcomes drawbacks of the prevalent joint probability contours (JPC) method by directly quantifying response variable extremes.

7) Knowledge Gaps and Improvements for Future Research

Our final objective is to reflect on the knowledge gaps in compound flood research and suggest potential directions for research going forward. Based on our detailed review we have five main recommendations moving forward, as follows:

Recommendation 1 - Adopt consistent definitions, terminology, and approaches: Definitions and use-cases of compound event, compound hazard, multi-hazard, and associated terminology (Table 1) are highly inconsistent throughout the literature (Kappes et al., 2012; Gallina et al., 2016; Tilloy et al., 2019). This is well recognized by Tilloy et al. (2019), who refer to the variety of terms as a "fragmentation of [the] literature." Similarly, Pescaroli and Alexander (2018) draw attention to trends in the "superficial" and "ambiguous" use of hazard terms by academics and practitioners. This tendency to use differing concepts synonymously is blurring the state of compound flood research (something we continuously observed while completing this review). They warn of potential confusion and duplication of research as a result of overlapping definitions. In summary, compound event and related terms have a wide range of overlapping and interlinked definitions, and there is a considerable need for clarity. Recent preliminary efforts by the collaborative MYRIAD-EU project to develop a multi-hazard and multi-risk definitions handbook appear promising for fostering a common understanding of hazard concepts across disciplines (Gill et al., 2020). Similarly, there is early collaborative work on the development of a compound flood practices manual and primer document as part of the ASCE-MOP project (Shields et al., 2023).

Recommendation 2 - Expand the geographic coverage of research: Geographically, much of the existing compound flood research is too narrowly focused on a select few regions (i.e., North America, Europe, Southeast Asia, the UK, China, the Netherlands, Australia) (Figure 3b). To date, there are no localized English-language studies, to our knowledge, on compound flooding in any parts of South America, Central America, or the Middle East. South America regularly experiences catastrophic flooding from both long-term heavy rainfall and extreme river discharge (e.g., 2015/16 (Reliefweb, 2016) and 2016/17 (Reliefweb, 2017) South American floods), however existing research in these regions has not considered their combined interactions. Furthermore, there are very few compound flood papers within the African subcontinent (Bischiniotis et al., 2018; De Michele et al., 2020; Van Berchum et al., 2020; Kupfer et al., 2022) (a region deserving of greater attention given the projected extreme coastal hazard exposure as a result of SLR, population growth, and coastal urbanization (Neumann et al., 2015)) due to a lack of data. While there are a handful of global studies, localized research on the interactions and dependence of flood variables is missing for many parts of the world. Future compound flood research must be dedicated to improving our understanding of these neglected regions including strategic data collection and developing methodologies for assessing compound flooding in data sparse areas.

Recommendation 3 - Pursue more inter-comparison and collaborative compound flood projects: Current methodologies for analysing compound flooding are highly diverse, inhibiting quantitative comparisons between studies. Considerable subjectivity is observed in compound event mechanism and variable selection, temporal and spatial bounds, hazard scenario design, conditional and joint probability, and dependence measurement (Zscheischler et al., 2020). Standard approaches for compound flood risk analysis have yet to be established (Kappes et al., 2012; Sebastian, 2022). Furthermore, methods for analysing compound events vary across scientific communities (Pietrafesa et al., 2019; Tilloy et al., 2019). Discussions involving emergency managers and stakeholders have revealed the leading barrier to the use of multi-hazard and multi-risk approaches was a lack of common methodologies and data (Komendantova et al., 2014). Further highlighting this point, Tilloy et al. (2019) identified a staggering 79 unique uses of 19 different methods for analysing compound events. There is a substantial need for a standardized framework that addresses assorted analytical methods and considerations (Sebastian, 2022) including flood variable choice and pairing, flood threshold definition, case study hazard design, spatiotemporal scales and resolutions, statistical model assumptions, numerical parameter choice, and interpretation of results. Future water management practices and coastal hazard mitigation strategies must better reflect the perspectives of compound events. To aid this we would recommend that the community develop educational training resources to guide the next generation of compound flood researchers. Furthermore, we suggest creating a compound flood inter-comparison project and associated working group, similar to that set up for the wave and coastal modelling communities (e.g., COWCLIP, (Hemer et al., 2010) and CoastMIP, (Hinkel et al., 2014)) and hydrological forecasting communities (e.g. HEPEX, (Schaake et al., 2007)).

Recommendation 4 - Develop modelling frameworks that holistically represent dynamic earth systems: While there have been substantial advancements in compound flood research over the past decade, the overall ability to identify, model, quantify, and forecast compound flood events remains a substantial challenge. These difficulties stem from the highly complex and chaotic nature of hydrological, meteorological, and oceanographic systems (Sebastian, 2022). Connections between flood modulators and drivers are spatiotemporally dynamic, and how those relationships are affected by the changing climate is uncertain and everchanging. Stand-alone numerical models generally lack the ability to holistically simulate the dynamic interconnected systems necessary to explain compound flooding (especially in the coastal setting). The skill of compound flood forecasting systems and numerical models has improved but still largely remains inadequate (Mashriqui et al., 2014; Pietrafesa et al., 2019). Going forward, we recommend the adoption of standardized modelling interfaces (e.g., Basic Model Interface (Hutton et al., 2020)) to facilitate coupling between numerical models to develop holistic modelling frameworks that better disentangle the complex earth system processes driving compound floods. We additionally suggest the development of ensemble forecast systems with ocean-land-atmosphere coupling and compound flood modelling in mind (e.g., Saleh et al. (2017); Blanton et al. (2018)). Compound flood research also serves to greatly benefit from the use of hybrid modelling frameworks that couple numerical and statistical models. While this review discovered many studies that employed hybrid numerical-statistical methods, few explicitly outlined a standardized frameworks for linking the models. Thus, we additionally recommend further evaluation of hybrid frameworks as the linking of statistical and numerical models has considerable room for improvement.

Recommendation 5 – Plan, design, and manage urban and coastal infrastructure with compound flooding in mind: We advise reshaping the planning, design, and operation of urban and coastal infrastructure to fully recognize the dependence and synergetic extremes of interacting flood drivers. As we look to a future of increasing flood frequency, proactive flood management is vital to lowering the vulnerability and exposure of urban and coastal communities. This can include investing in long-term resilient infrastructure (i.e., >100-year extremes), developing flood hazard maps that consider compound flood return periods to aid planning (e.g. update FEMA hazard maps), supporting development blue-green and natural flood management (e.g., wetland protection, riverbank restoration, and leaky dams), enacting operational early warning systems (e.g. coupled ensemble forecast systems, (Saleh et al., 2017)) and emergency response measures, and educating the public about the risks of inhabiting coastal floodplains.

8) Conclusions

We have long known that high-impact hazard events involve a combination of drivers, however existing research has largely been limited to single-factor or univariate analysis of climate extremes due to technical or methodological constraints. Such is the case with flooding, as standard flood hazard assessment practices have traditionally accounted for the effects of the different drivers of flooding independently. Only in recent years has flood research more closely examined the non-linear combination of these variables through the lens of compound events.

This paper has presented a systematic review of the existing literature on compound flooding in coastal regions. Analysis of 279 studies up to and including the year 2022 has revealed significantly increasing attention to compound flood research in recent years. This review identified different definitions and terminologies of compound flood events, categories of compound flood drivers, numerical modelling frameworks, and statistical analysis techniques. Furthermore, several compound flood hotspots have been identified throughout the world including the US East Coast and Gulf of Mexico, Northern Europe, East Asia, Southern Asia, Southeast Asia, Northern Australia, and global low-lying deltas and estuaries. Research has shown that compound floods are likely to have increasing frequency and severity in the future as a result of climate change, and that societal risks of extreme climate hazards are underestimated when the compound effects of climatic processes are not considered in combination. Compound flood research thus requires a more holistic and integrated approach to risk analysis that reflects on the complex interactions and nonstationary of Earth systems. We must recognize the threats posed by the interactions between hazard drivers for accurate risk assessment. Further research must also focus on identifying the dominant drivers of flooding, the precursors that make certain regions particularly susceptible to compound flooding, the dependence relationships between flood drivers, and investigate how all these aspects change spatiotemporally. Going forward, an improved understanding of compound flooding processes and precursors is vital to coastal management, hazard risk reduction, and community resilience in the face of changing climates.

Acknowledgments

We thank Kate Davis[1] for the creation of the schematic diagram (Figure 1). JG time was supported by the UKRI Natural Environmental Research Council (NERC) grant NE/S007210/1. IDH time was supported by NERC grant NE/S010262/1. JN time was supported by the NERC grant NE/S015639/1. TW acknowledges support from the National Science Foundation (grant no. 1929382 and 2103754) and the USACE Climate Preparedness and Resilience Community of Practice and Programs. PJW and MCdR received support from the MYRIAD-EU project, which received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 101003276. MCdR also received support from the Netherlands Organisation for Scientific Research (NWO) (VENI; grant no. VI.Veni.222.169). PC recognizes funding from the MyFlood project (PLEC2022-009362 - MCIN/AEI/10.13039/501100011033 and European Union Next GenerationEU/PRTR).

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Competing Interests

Co-author Philip Ward is a member of the NHESS editorial board.

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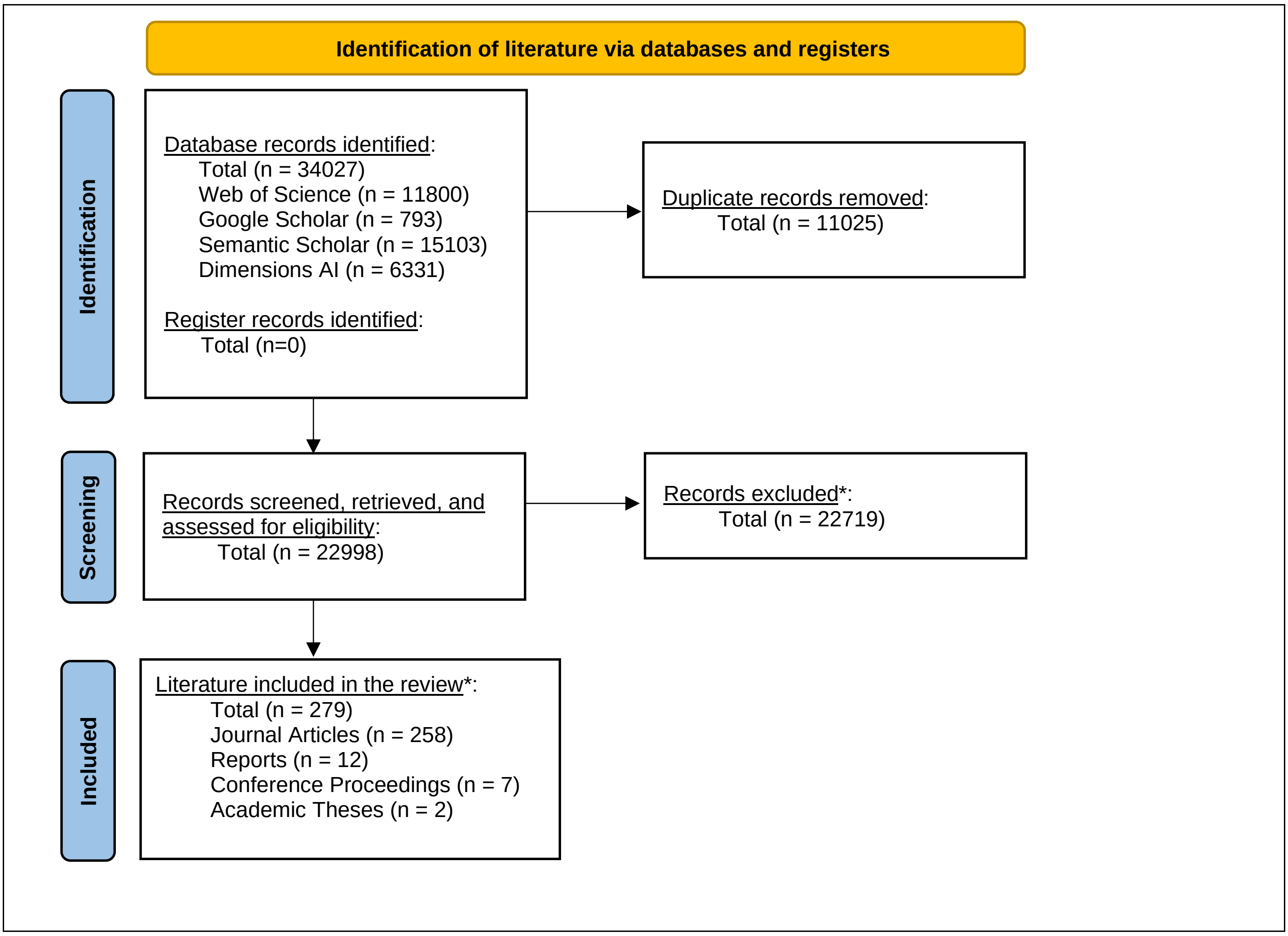
Appendix

Figure A1. PRISMA 2020 flow diagram (Page et al., 2021) visualizing the review's literature database curation process. This includes the number of papers: identified in literature databases using the search terms in Table 2; removed due to being a duplicate; screened against scoping criteria as outlined in Section 4; excluded from consideration; and included in the review analysis.



*The criteria for including or excluding literature records is defined in Section 4.

Table A1. Overview of the literature database containing 279 compound flood research publications. Note: Numerical models without defined names are given simple descriptions. Statistical methods are defined as explicitly stated in the literature and then simplified for brevity.

Author	Geographic Region	Scenario / Event	Application	Compound Drivers	Numerical	Statistical	Numerical & Statistical	Numerical Models	Statistical Methods / Tools
Acreman 1994	UK (River Roding)	Varying climate change scenarios, Varying return period scenarios	Planning & Management, Risk Assessment	Fluvial, Coastal	TRUE	TRUE	TRUE	ONDA	Joint Probability Method (JPM)
Ai et al. 2018	China (Jiangsu)	-	Risk Assessment	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula
Apel et al. 2016	Vietnam (Can Tho, Mekong Delta)	-	Risk Assessment	Fluvial, Pluvial	TRUE	TRUE	TRUE	2D Hydrodynamic Model	Joint Probability Method (JPM), Copula
Archetti et al. 2011	Italy (Rimini)	-	Planning & Management, Risk Assessment	Pluvial, Coastal	TRUE	TRUE	TRUE	1D Hydrodynamic Drainage Model (InfoWorks CS)	Joint Probability Method (JPM), Copula
Bacopoulos et al. 2017	US (Florida)	Tropical Storm Fay (2008)	Risk Assessment	Fluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, SWAT	-
Bakhtyar et al. 2020	US (Delaware, Delaware Bay)	-	Forecasting	Fluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, D-FLOW FM, HEC-RAS, NWM, WW3	-
Ballesteros et al. 2018	Spain (Maresme Coast)	Varying return period scenarios	Risk Assessment	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Source-Pathway-Receptor-Consequence Model (SPRC), Index Analysis (Flood Risk Index, Flash Flood Potential Index (FFPI), Exposure Index, Social Vulnerability Index)
Banfi and Michele 2022	Italy (Lake Como)	Lake Flood Events (1980 -2020)	Earth System Processes	Pluvial	FALSE	TRUE	FALSE	-	Temporal Analysis (Clustering)
Bao et al. 2022	US (North Carolina, Cape Fear River Basin)	Hurricane Florence (2018)	Methodological Advancement	Pluvial, Coastal	TRUE	FALSE	FALSE	COAWST	-
Bass and Bedient 2018	US (Texas)	Tropical Storm Allison (2001), Hurricane Ike (2008)	Forecasting, Risk Assessment	Pluvial, Coastal	TRUE	TRUE	TRUE	ADCIRC, HEC-HMS, HEC-RAS, SWAN	Machine Learning (Artificial Neural Networks (ANN)), Storm Surge Statistical Emulator (Kriging/Gaussian Process Regression (GPR)), Principal Components Analysis, Bayesian Regularization Algorithm
Bates et al. 2021	US (CONUS)	Varying climate change scenarios	Methodological Advancement	Fluvial, Pluvial, Coastal	TRUE	FALSE	FALSE	LISFLOOD-FP	-
Bayazıt and Koç 2022	Turkey (Marmaris, Marmaris Bay)	Dec 4, 2021 Flood Event; Summer 2021 Fires	Earth System Processes	Pluvial, Fire	TRUE	TRUE	TRUE	SWAT	Soil Conservation Service–Curve Number (SCS–CN)
Beardsley et al. 2013	US (Massachusetts)	2010 Nor'easter Storm	Forecasting	Fluvial, Coastal	TRUE	FALSE	FALSE	FVCOM	-
Benestad and Haugen 2007	Norway	-	Earth System Processes	Pluvial, Temp/Heat, Snow	FALSE	TRUE	FALSE	ECHAM4, HIRHAM	Joint Probability Method (JPM), Monte Carlo Simulation

Author	Geographic Region	Scenario / Event	Application	Compound Drivers	Numerical	Statistical	Numerical & Statistical	Numerical Models	Statistical Methods / Tools
Bermúdez et al. 2019	Spain (Betanzos, Mandeo River)	-	Earth System Processes, Methodological Advancement	Fluvial, Coastal	TRUE	TRUE	TRUE	Iber	Least Square Support Vector Machine (LS-SVM) Regression
Bermúdez et al. 2021	Spain (Betanzos, Mandeo River)	Varying climate change scenarios	Earth System Processes, Methodological Advancement	Fluvial, Pluvial, Coastal, Temp/Heat	TRUE	TRUE	TRUE	Iber, MISDc	Machine Learning (Artificial Neural Networks (ANN)), Least Square Support Vector Machine (LS-SVM) Regression, Bayesian Regularization Algorithm
Bevacqua et al. 2017	Italy (Ravenna)	February 2015 Flood Event	Risk Assessment	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Linear Gaussian Autoregressive Model
Bevacqua et al. 2019	Europe	Varying climate change scenarios, Varying return period scenarios	Earth System Processes, Risk Assessment	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula
Bevacqua et al. 2020a	Global	Varying climate change scenarios	Earth System Processes	Pluvial, Coastal	TRUE	TRUE	TRUE	Delft3D-FLOW	Joint Probability Method (JPM), Copula
Bevacqua et al. 2020b	Global	Varying return period scenarios	Risk Assessment	Fluvial, Pluvial	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula
Bevacqua et al. 2022	Australia (Perth, Swan River)	-	Risk Assessment	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Multivariate Non-linear Regression, Copula, Temporal Analysis, Kendall's Correlation Coefficient tau (τ), Tail Dependence Coefficient (λ)
Bilskie et al. 2021	US (Louisiana, Barataria and Lake Maurepas Watersheds)	21 Tropical Cyclone Events (1948–2008)	Methodological Advancement	Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC	-
Bischiniotis et al. 2018	Africa (Sub-Saharan Region)	501 Flood Events (1980 - 2010)	Forecasting, Risk Assessment	Pluvial, Soil Moisture	FALSE	TRUE	FALSE	-	Temporal Analysis, Risk Ratio (RR)
Blanton et al. 2012	US (North Carolina)	Hurricane Irene (2011)	Forecasting, Planning & Management	Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, HL-RDHM	-
Blanton et al. 2018	US (North Carolina)	Hurricane Isabel (2003)	Forecasting, Planning & Management	Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, CREST, WRF	-
Bliskie and Hagen, 2018	US (Louisiana)	Hurricane Gustav (2008) and 2016 Flood Event	Risk Assessment	Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC	-
Brown et al. 2007	UK (Canvey Island)	-	Methodological Advancement	Coastal	TRUE	FALSE	FALSE	Delft-FLS, SWAN	-
Bunya et al. 2010	US (Louisiana and Mississippi)	-	Methodological Advancement	Fluvial, Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, ECWAM, H*WIND, IOKA, STWAVE,	-
Bush et al. 2022	US (North Carolina)	-	Methodological Advancement	Fluvial, Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, HEC-RAS	-

Author	Geographic Region	Scenario / Event	Application	Compound Drivers	Numerical	Statistical	Numerical & Statistical	Numerical Models	Statistical Methods / Tools
Camus et al. 2021	Europe	-	Earth System Processes	Fluvial, Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Spatial Analysis, Correlation Coefficients (Kendall's tau (τ), Spearman's rho (ρ))
Camus et al. 2022	Global (US and Europe, North Atlantic)	Flood Events (1980-2014)	Earth System Processes	Fluvial, Coastal	TRUE	TRUE	TRUE	CaMa-Flood, GTSM	Joint Occurrence Method, Spatial Analysis (Clustering K-Means Algorithm (KMA)), Principal Component Analysis (PCA), Temporal Analysis, Kendall's Correlation Coefficient tau (τ)
Cannon et al. 2008	US (California)	2003 Piru, Old, and Grand Prix Fires; 2023/24 Winter Storms	Earth System Processes	Pluvial, Fire	FALSE	TRUE	FALSE	-	Spatial Analysis, Temporal Analysis
Čepienė et al. 2022	Lithuania (Klaipėda)	-	Risk Assessment	Fluvial, Coastal	TRUE	FALSE	FALSE	HEC-RAS	-
Chen and Liu 2014	Taiwan (Tainan City, Tsengwen River basin)	Typhoon Krosa (2007), Kalmegei (2008), Morakot (2009), and Haiyan (2013)	Methodological Advancement	Fluvial, Coastal	TRUE	FALSE	FALSE	SELFE	-
Chen and Liu, 2016	Taiwan (Kaohsiung City, Gaoping River)	Typhoon Kalmegei (2008), Morakot (2009), Fanapi (2010), Nanmadol (2011), and Talim (2012), Varying return period scenarios	Risk Assessment	Fluvial, Coastal	TRUE	FALSE	FALSE	SELFE	-
Chen et al. 2010	UK (Bradford, Keighley, River Aire)	Varying return period scenarios	Planning & Management, Risk Assessment	Fluvial, Pluvial	TRUE	FALSE	FALSE	SIPSON, UIM	-
Chen et al. 2013	Taiwan (Tainan City)	Typhoon Haitang (2005) and Kalmaegi (2008), Varying return period scenarios	Risk Assessment	Pluvial, Coastal	TRUE	FALSE	FALSE	SELFE	-
Chou 1989	Saipan (West Coast)	168 Synthetic Typhoon Events, Varying return period scenarios	Risk Assessment	Coastal	TRUE	TRUE	TRUE	SHAWLWV, WIFM	Joint Probability Method (JPM), Frequency Analysis
Christian et al. 2015	US (Texas, Galveston Bay)	Hurricane Ike (2008)	Planning & Management	Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, HEC-RAS, Vflo	-
Cifelli et al. 2021	US (California, San Francisco)	-	Forecasting	Fluvial, Coastal	TRUE	FALSE	FALSE	Hydro-CoSMoS	-
Coles and Tawn 1994	UK (Cornwall)	-	Methodological Advancement, Risk Assessment	Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Chi-Squared Test (χ2)
Coles et al. 1999	UK (Southwest Coast)	-	Methodological Advancement, Risk Assessment	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Chi-Squared Test (χ2)
Comer et al. 2017	Ireland (Cork City)	2009 Flood Event	Methodological Advancement	Fluvial, Coastal	TRUE	FALSE	FALSE	MSN_Flood, POM	-
Couasnon et al. 2018	US (Texas)	-	Methodological Advancement, Risk Assessment	Fluvial, Coastal	TRUE	TRUE	TRUE	1D Hydrodynamic Model	Bayesian Network (BN), Copula

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Couasnon et al. 2020	Global	-	Earth System Processes	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Spatial Analysis, Temporal Analysis, Spearman's Correlation Coefficient rho (ρ)
Curtis et al. 2022	US (North Carolina)	-	Risk Assessment	Fluvial, Coastal	FALSE	FALSE	FALSE	-	-
Daoued et al. 2021	France (Le Havre)	Varying return period scenarios	Risk Assessment	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Probabilistic Flood Hazard Assessment (PFHA), Belief Functions
De Bruijn et al. 2014	Netherlands (Rhine-Meuse delta)	-	Risk Assessment	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Copula, FN-Curve, Potential Loss of Life (PLL), Monte Carlo Simulation
De Michele et al. 2020	Global (Europe and North Africa)	-	Earth System Processes	Pluvial	FALSE	TRUE	FALSE	-	Copula, Binary Markov Chain Network, Monte Carlo Simulation
Deidda et al. 2021	UK	-	Earth System Processes	Fluvial, Pluvial	FALSE	TRUE	FALSE	-	Joint Occurrence Method, Spatial Analysis, Kendall's Correlation Coefficient tau (τ)
Del-Rosal-Salido et al. 2021	Europe (Iberian Peninsula, Guadalete Estuary)	Varying climate change scenarios, Varying return period scenarios	Forecasting, Planning & Management	Fluvial, Coastal	TRUE	TRUE	TRUE	Delft3D	Spatial Analysis (Vector Autoregressive (VAR) Model)
Dietrich et al. 2010	US (Louisiana and Mississippi)	Hurricane Katrina (2005) and Rita (2005)	Methodological Advancement	Fluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, IOKA, H*WIND, STWAVE, WAM	-
Dixon and Tawn 1994	UK	-	Earth System Processes	Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Extreme Value Analysis, Chi-Squared Test (χ2)
Dresback et al. 2013	US (North Carolina)	Hurricane Irene (2011)	Forecasting	Fluvial, Coastal	TRUE	FALSE	FALSE	ASGS-STORM, ADCIRC, Holland Wind Model, HL-RDHM, SWAN	-
Dykstra et al. 2021	US (Gulf Coast; Ascagoula, Tombigbee-Alabama River, and Apalachicola watersheds)	-	Earth System Processes	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Kendall's Correlation Coefficient tau (τ), Frequency Analysis, Temporal Analysis (Pettitt Test), Wavelet Transformations (Mortlet-type Wave), Bootstrap Method
Eilander 2022	Global	-	Earth System Processes, Risk Assessment	Fluvial, Coastal	TRUE	TRUE	TRUE	Delft-FIAT, HydroMT	Joint Probability Method (JPM), Copula, Extreme Value Analysis
Eilander et al. 2020	Global	-	Earth System Processes, Risk Assessment	Fluvial, Coastal	TRUE	FALSE	FALSE	CaMa-Flood, FES2012, GTSM	-
Eilander et al. 2022	Mozambique (Sofala)	Varying return period scenarios	Impact Assessment, Risk Assessment	Fluvial, Pluvial, Coastal	TRUE	TRUE	TRUE	CaMa-Flood, Delft-FIAT, SFINCS	Copula, Block Maxima
Erikson et al. 2018	US (California, San Francisco)	Varying climate change scenarios, Varying return period scenarios	Impact Assessment, Risk Assessment	Fluvial, Coastal	TRUE	FALSE	FALSE	CoSMoS	-

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Familkhalili et al. 2022	US (North Carolina, Cape Fear Estuary)	Hurricane Irene (2011)	Earth System Processes	Fluvial, Coastal	TRUE	FALSE	FALSE	1D Hydrodynamic Model	-
Fang et al. 2021	China	Varying climate change scenarios, Varying return period scenarios	Earth System Processes	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Kendall's Correlation Coefficient tau (τ), Temporal Analysis, Peak-over-Threshold (POT)
Feng and Brubaker, 2016	US (Washington DC)	Varying climate change scenarios, Varying return period scenarios	Impact Assessment, Risk Assessment	Pluvial, Coastal	TRUE	FALSE	FALSE	HEC-RAS	-
Ferrarin et al. 2022	Italy (Venice, Adriatic Sea)	November 2019 Flood Event	Earth System Processes, Risk Assessment	Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Kendall's Correlation Coefficient tau (τ), Temporal Analysis, Mann-Whitney U Test
Flick 1991	US (California, San Francisco)	-	Risk Assessment	Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM)
Galiatsatou and Prinos 2016	Greece (Aegean Sea)	-	Earth System Processes	Coastal	TRUE	TRUE	TRUE	RegCM3, SWAN	Joint Probability Method (JPM), Copula, Block Maxima
Ganguli and Merz 2019a	Europe (Northwest)	-	Earth System Processes	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Spatial Analysis, Compound Hazard Ratio (CHR) Index, Kendall's Correlation Coefficient tau (τ)
Ganguli and Merz 2019b	Europe (Northwest)	Flood Events (1970-2014)	Earth System Processes	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Spatial Analysis, Frequency Analysis, Compound Hazard Ratio (CHR) Index, Kendall's Correlation Coefficient tau (τ)
Ganguli et al. 2020	Europe (Northwest)	Varying climate change scenarios	Earth System Processes	Fluvial, Coastal	TRUE	TRUE	TRUE	Delft3D-FLOW, WGHM	Copula, Markov Chain, Monte Carlo Simulation
Georgas et al. 2016	US (New York and New Jersey)	Winter Storm Jonas (2016)	Forecasting	Fluvial, Coastal	TRUE	FALSE	FALSE	ESTOFS, ETSS, sECOM, SFAS, NAM, NYHOPS	-
Ghanbari et al. 2021	US (CONUS)	Varying return period scenarios, Varying climate change scenarios	Earth System Processes, Risk Assessment	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Quantile Regression, Kendall's Correlation Coefficient tau (τ), Peak-over-Threshold (POT)
Gori and Lin 2022	US (North Carolina, Cape Fear River)	Varying climate change scenarios	Risk Assessment	Fluvial, Pluvial, Coastal	TRUE	TRUE	TRUE	ADCIRC, HEC-HMS, HEC-RAS	Joint Probability Method Optimal Sampling Bayesian Quadrature Optimization (JPM-OS-BQ)
Gori et al. 2020a	US (North Carolina, Cape Fear River)	Varying return period scenarios	Earth System Processes	Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, HEC-HMS, HEC-RAS	-
Gori et al. 2020b	US (North Carolina, Cape Fear River)	Tropical Cyclone Fran (1996), Floyd (1999), and Matthew (2016), Varying return period scenarios	Earth System Processes	Fluvial, Pluvial, Coastal	TRUE	TRUE	TRUE	ADCIRC, HEC-HMS, HEC-RAS	Joint Probability Method (JPM), Copula
Gori et al. 2022	US (East and Gulf Coast)	Varying climate change scenarios, Varying return period scenarios	Risk Assessment	Pluvial, Coastal	TRUE	TRUE	TRUE	ADCIRC	Joint Probability Method (JPM), Kendall's Correlation Coefficient tau (τ), Statistical-Deterministic TC Model, Spatial Analysis, Temporal Analysis, Bootstrap Method

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Gouldby et al. 2017	UK (South Coast)	Varying return period scenarios	Methodological Advancement	Coastal	TRUE	TRUE	TRUE	SWAN, WW3	Joint Probability Method (JPM), Wave Transformation Model Emulator, Monte Carlo Simulation
Gutenson et al. 2022	US (Texas, Galveston Bay)	Hurricane Harvey (2017)	Impact Assessment, Methodological Advancement, Risk Assessment	Fluvial, Pluvial, Coastal	TRUE	TRUE	TRUE	AutoRoute, HEC-RAS, LISFLOOD-FP	Spatial Analysis
Habel et al. 2020	US (Hawaii, Honolulu)	Varying climate change scenarios, Varying return period scenarios	Impact Assessment, Planning & Management	Coastal, Groundwater	TRUE	TRUE	TRUE	MODFLOW	Frequency Analysis, Bayesian Hierarchical Model, Spatial Analysis
Haigh et al. 2016	UK	2013-2014 Winter Storm Season	Earth System Processes	Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Spatial Analysis, Temporal Analysis, Peak-over-Threshold (POT)
Harrison et al. 2022	UK (Humber and Dyfi Estuaries)	-	Earth System Processes	Fluvial, Pluvial, Coastal	TRUE	FALSE	FALSE	2D Hydrodynamic Model	-
Hawkes 2003	UK	-	Earth System Processes, Methodological Advancement	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), JOIN-SEA Model
Hawkes 2006	UK	-	Planning & Management, Risk Assessment	Fluvial, Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), JOIN-SEA Model, Chi-Squared Test (χ2)
Hawkes 2008	UK (South Coast)	-	Methodological Advancement, Risk Assessment	Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), JOIN-SEA Model, Temporal Analysis, Monte Carlo Simulation
Hawkes and Svensson 2003	UK	-	Earth System Processes, Risk Assessment	Fluvial, Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), JOIN-SEA Model, Monte Carlo Simulation
Hawkes et al. 2002	UK (England and Wales)	Varying return period scenarios	Risk Assessment	Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Monte Carlo Simulation
Helaire et al. 2020	US (Washington, Portland-Vancouver, Columbia River Estuary)	Varying climate change scenarios	Earth System Processes	Fluvial, Coastal	TRUE	FALSE	FALSE	Delft3D	-
Hendry et al. 2019	UK	-	Earth System Processes	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Occurrence Method, Kendall's Correlation Coefficient tau (τ), Temporal Analysis, Block Maxima, Peak-over-Threshold (POT)
Herdman et al. 2018	US (California, San Francisco)	-	Forecasting	Fluvial, Coastal	TRUE	FALSE	FALSE	Delft3D-FM	-
Ho and Myers 1975	US (Florida, St. George Sound, Apalachicola Bay)	Varying return period scenarios	Methodological Advancement, Risk Assessment	Coastal	TRUE	TRUE	TRUE	SPLASH, 2D Hydrodynamic Bay-Ocean Model (Overland 1975)	Joint Probability Method (JPM), Frequency Analysis
Hsiao et al. 2021	Taiwan	Typhoon Mindulle (2004), Typhoon Morakot (2009), Typhoon Megi (2016), Low-Pressure Rainstorm (2018),	Risk Assessment	Fluvial, Pluvial, Coastal	TRUE	TRUE	TRUE	SCHISM, COS-Flow, 39 GCMs	Index Analysis (2 Hazard Indices, 4 Exposure Indices, 6 Vulnerability Indices)

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		Varying climate change scenarios							
Huang 2022	Taiwan (Touqian and Fengshan Rivers)	Hurricane Harvey (2017)	Forecasting	Pluvial, Coastal	TRUE	TRUE	TRUE	ADCIRC	Machine Learning (Recurrent Neural Network (RNN)), Topographic Wetness Index (TWI)
Huang et al. 2021	US (Texas, Galveston Bay)	-	Earth System Processes	Fluvial, Pluvial, Coastal	TRUE	TRUE	TRUE	SCHISM	Compound Ratio (CR), Spatial Analysis
Ikeuchi et al. 2017	Bangladesh (Ganges-Brahmaputra-Meghna Delta)	Cyclone Sidr (2007)	Methodological Advancement	Fluvial, Coastal	TRUE	FALSE	FALSE	CaMa-Flood, MATSIRO-GW	-
Jalili Pirani and Reza Najafi 2020	Canada	-	Earth System Processes	Fluvial, Pluvial, Coastal	FALSE	TRUE	FALSE	-	Spatial Analysis, Temporal Analysis (Mann-Kendall Test), Probability Space (PS) Index, Correlation Coefficients (Kendall's tau (τ), Spearman's rho (ρ))
Jalili Pirani and Reza Najafi 2022	Canada (East and West Coast, Great Lakes)	Varying return period scenarios	Earth System Processes	Fluvial, Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Compound Hazard Ratio (CHR) Index, Copula, Kendall's Correlation tau (τ)
Jane et al. 2020	US (Florida)	-	Earth System Processes	Pluvial, Coastal, Groundwater	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Kendall's Correlation Coefficient tau (τ)
Jane et al. 2022	US (Texas, Sabine and Brazos River Basins)	Varying return period scenarios	Planning & Management, Risk Assessment	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Peak-over-Threshold (POT)
Jang and Chang 2022	Taiwan (Chiayi)	Varying return period scenarios	Risk Assessment	Pluvial, Coastal	TRUE	TRUE	TRUE	COS-Flow	Joint Probability Method (JPM), Copula, Monte Carlo Simulation
Jasim et al. 2020	US (California, Sherman Island)	Varying return period scenarios	Planning & Management, Risk Assessment	Fluvial, Pluvial	TRUE	TRUE	TRUE	RS3	Joint Probability Method (JPM), Frequency Analysis, Copula
Jones 1998	UK (Thames Estuary)	-	Earth System Processes, Methodological Advancement	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Temporal Analysis, Historical Emulation Model
Jong-Levinger et al. 2022	US (California)	Varying climate change scenarios, Varying return period scenarios	Earth System Processes	Pluvial, Fire	FALSE	TRUE	FALSE	-	Markov Chain Monte Carlo (MCMC) Algorithm
Joyce et al. 2018	US (Florida)	Varying climate change scenarios	Methodological Advancement, Risk Assessment	Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, SWAN, ICPR	-
Juárez et al. 2022	US (Florida, Jacksonville, Lower St. Johns River)	Hurricane Irma (2017), Varying climate change scenarios	Earth System Processes, Methodological Advancement	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Flow Interaction Ratio Index (μ), Temporal Analysis
Karamouz et al. 2014	US (New York, New York City)	Varying return period scenarios, Varying climate change scenarios	Planning & Management	Pluvial, Coastal	TRUE	TRUE	TRUE	HEC-RAS, GSSHA, SWMM	Machine Learning (Multilayer Perceptron (MLP) Feedforward Neural Network (FNN)), Markov Chain Monte Carlo (MCMC) Algorithm, DREAM_ZS, Max Relevance Min Redundancy (MRMR) Algorithm

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Karamouz et al. 2017	US (New York, New York City)	Hurricane Irene (2011) and Sandy (2012), Varying future climate change flood scenarios, Varying return period scenarios	Methodological Advancement	Pluvial, Coastal	TRUE	TRUE	TRUE	GSSHA	Joint Probability Method (JPM), Frequency Analysis, Copula
Karamouz et al. 2017	US (New York, New York City)	Varying return period scenarios	Impact Assessment, Risk Assessment	Pluvial, Coastal	TRUE	TRUE	TRUE	GSSHA	Joint Probability Method (JPM), Frequency Analysis, Flood Damage Estimator (FDE) Model, Copula, Correlation Coefficients (Kendall's tau (τ), Pearson's (r), Spearman's rho (ρ))
Kerr et al. 2013	US (Louisiana and New Orleans, Mississippi River)	Hurricane Betsy (1965), Camille (1969), Andrew (1992), Katrina (2005), Rita (2005), Gustav (2008), Ike (2008), and 15 Synthetic Storm Events	Earth System Processes	Fluvial, Coastal	TRUE	TRUE	TRUE	ADCIRC, H*WIND, SWAN	Joint Probability Method (JPM) with Optimal Sampling (JPM-OS), Frequency Analysis
Kew et al. 2013	Netherlands (Rhine Delta)	Varying return period scenarios, Varying climate change scenarios	Earth System Processes	Fluvial, Coastal	TRUE	TRUE	TRUE	ECHAM5, MPI-OM	Joint Probability Method (JPM), Extreme Value Analysis, Peak-over-Threshold (POT)
Khalil et al. 2022	Australia (Brisbane, Brisbane River and Moreton Bay)	Flood Events (2006, 2011, 2013)	Earth System Processes, Methodological Advancement	Fluvial, Coastal	TRUE	FALSE	FALSE	MIKE21	-
Khanal et al. 2019	Europe (Rhine River Basin)	-	Earth System Processes	Fluvial, Coastal	TRUE	TRUE	TRUE	DCSM, HBV, RACMO2, SPHY, WAQUA	Joint Probability Method (JPM), Temporal Analysis
Khanam et al. 2021	US (Connecticut)	Varying climate change scenarios	Impact Assessment, Risk Assessment	Pluvial, Coastal	TRUE	FALSE	FALSE	CREST-SVAS, HEC-RAS, WRF	-
Khatun et al. 2022	India (Upper Mahanadi River basin)	Varying return period scenarios, Varying climate change scenarios	Earth System Processes	Fluvial, Pluvial	TRUE	TRUE	TRUE	MIKE11, NAM	Bivariate Hazard Ratio (BHR) Index, Copula, Kendall's Correlation Coefficient tau (τ), Peak-over-Threshold (POT)
Kim and Sanders 2016	South Korea (Gangneung, Seomseok River, Geumgwang River)	Typhoon Rusa (2002), August 31 Dam Break (Janghyeon Dam, Dongmak Dam)	Methodological Advancement	Pluvial, Coastal, Damming/ Dam Failure	TRUE	FALSE	FALSE	BreZo, HEC-HMS	-
Kim et al. 2022	US (Texas, Houston, Dickinson Bayou Watershed)	Hurricane Harvey (2017)	Earth System Processes	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Copula, Kendall's Correlation Coefficient tau (τ), Peak-over-Threshold (POT)
Kirkpatrick and Olbert 2020	Ireland (Cork City)	Varying climate change scenarios, Varying return period scenarios	Earth System Processes, Risk Assessment	Fluvial, Coastal	TRUE	FALSE	FALSE	-	-
Klerk et al. 2015	Netherlands (Hoek van Holland and Lobith, Rhine-Meuse Delta)	Varying climate change scenarios, Varying return period scenarios	Earth System Processes	Fluvial, Coastal	FALSE	TRUE	FALSE	CKF, Delft3D-FLOW, DCSM, HBV-96	Temporal Analysis, Chi-Squared Test (χ2), Peak-over-Threshold (POT)
Kowalik and Proshutinsky 2010	US (Alaska, Cook Inlet)	-	Earth System Processes	Coastal, Tsunami	TRUE	FALSE	FALSE	1D/2D Hydrodynamic Models	-
Kudryavtseva et al. 2020	Europe (Baltic Sea)	-	Risk Assessment	Coastal	TRUE	TRUE	TRUE	NEMO, WAM	Joint Probability Method (JPM), Copula

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Kumbier et al. 2018	Australia (New South Wales, Nowra, Shoalhaven River)	2016 Cyclone	Earth System Processes, Risk Assessment	Fluvial, Coastal	TRUE	FALSE	FALSE	Delft3D-FLOW	-
Kupfer et al. 2022	South Africa (Breede Estuary)	Varying return period scenarios	Earth System Processes, Risk Assessment	Fluvial, Coastal	TRUE	FALSE	FALSE	Delft3D-FLOW, Delft3D-WAVE	-
Lai et al. 2021a	Global	-	Earth System Processes, Risk Assessment	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Kendall's Correlation Coefficient tau (τ), Peak-over-Threshold (POT)
Lai et al. 2021b	Global	Varying climate change scenarios, Varying return period scenarios, Flood Events (1948–2014, 1979–2014)	Earth System Processes	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Frequency Analysis, Spatial Analysis, Temporal Analysis (Mann-Kendall Test), Multivariate Regression, Peak-over-Threshold (POT)
Láng-Ritter et al. 2022	Spain	-	Forecasting, Impact Assessment, Risk Assessment	Fluvial, Pluvial	TRUE	FALSE	FALSE	EFAS, ReAFFIRM	-
Latif and Simonovic 2022a	Canada (West Coast)	-	Methodological Advancement, Risk Assessment	Fluvial, Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula
Latif and Simonovic 2022b	Canada (West Coast)	-	Methodological Advancement, Risk Assessment	Fluvial, Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula
Lawrence et al. 2014	Norway	Varying return period scenarios	Risk Assessment	Pluvial, Snow	TRUE	TRUE	TRUE	HBV, PQRUT	Stochastic Probability (SCHADEX Probabilistic Method, GRADEX Probabilistic Method)
Lee et al. 2019	South Korea	Typhoon Maemi (2003)	Methodological Advancement, Risk Assessment	Fluvial, Coastal	TRUE	FALSE	FALSE	Delft3D, HEC-HMS	-
Lee et al. 2020	South Korea (Busan, Marine City)	-	Methodological Advancement	Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, FLOW-3D, SWAN, XPSWMM	-
Leijnse et al. 2021	US (Florida, Jacksonville) and Phillippines	Hurricane Irma (2017) and Typhoon Haiyan (2013)	Methodological Advancement	Fluvial, Pluvial, Coastal	TRUE	FALSE	FALSE	SFINCS	-
Li and Jun 2020	South Korea (Han River)	-	Earth System Processes, Risk Assessment	Fluvial, Coastal	TRUE	FALSE	FALSE	1D Hydrodynamic Model	-
Li et al. 2022	Hong Kong (Hong Kong-Zhuhai-Macao Bridge)	-	Risk Assessment	Pluvial, Coastal	TRUE	TRUE	TRUE	MIKE+	Joint Probability Method (JPM), Temporal Analysis, Damage Curves
Lian et al. 2013	China (Fuzhou City)	Typhoon Longwang (2005), Varying return period scenarios	Risk Assessment	Pluvial, Coastal	TRUE	TRUE	TRUE	HEC-RAS, SWAT	Joint Probability Method (JPM), Copula, Peak-over-Threshold (POT)
Lian et al. 2017	China (Hainan Province, Haikou)	-	Planning & Management, Risk Assessment	Pluvial, Coastal	TRUE	TRUE	TRUE	HEC-RAS, SWMM	Disaster Reduction Analysis, Cost-Benefit Analysis (CBA)

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Liang and Zhou 2022	China (Zhejiang, Qiantang River)	Typhoon Lekima (2019)	Methodological Advancement, Risk Assessment	Fluvial, Coastal	TRUE	FALSE	FALSE	CaMa-Flood, MIKE21	-
Lin et al. 2010	US (East Coast, Chesapeake Bay)	-	Earth System Processes	Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, WRF	-
Liu et al. 2022	China (Haikou City)	-	Risk Assessment	Pluvial, Coastal	TRUE	FALSE	FALSE	Delft3D	-
Loganathan et al. 1987	US (Virginia, Rappahannock River)	-	Earth System Processes, Risk Assessment	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Box-Cox Transformation, Chi-Squared Test (χ2)
Loveland et al. 2021	US (Texas, Lower Neches River)	Hurricane Harvey (2017)	Methodological Advancement	Fluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, HEC-RAS	-
Lu et al. 2022	China (Southeast)	-	Risk Assessment	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Multivariate Copula Analysis Toolbox (MvCAT), Kendall’s Correlation Coefficient tau (τ)
Lucey et al. 2022	US (California, Los Angeles, Huntington Beach, San Diego)	Varying return period scenarios	Risk Assessment	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Copula, Correlation Coefficients (Kendall’s tau (τ), Pearson’s (r), Spearman’s rho (ρ))
Lyddon et al. 2022	UK	-	Earth System Processes, Methodological Advancement	Coastal	FALSE	TRUE	FALSE	-	Frequency Analysis, Temporal Analysis, Spatial Analysis, Kendall’s Correlation Coefficient tau (τ), Annual Mean Compound Event Measure, Block Maxima, Peak-over-Threshold (POT)
Manoj et al. 2022	India	-	Earth System Processes	Pluvial, Soil Moisture	FALSE	TRUE	FALSE	-	Event Coincidence Analysis (ECA), Chi-Squared Test (χ2), Spatial Analysis, Temporal Analysis
Mantz and Wakeling 1979	UK (Norfolk, Yare Basin)	Varying return period scenarios	Planning & Management, Risk Assessment	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Extreme Value Analysis
Martyr et al. 2013	US (Louisiana)	Hurricane Gustave (2008)	Methodological Advancement	Fluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC	-
Mashriqui et al. 2010	US (Washington DC)	1996 Flood, Hurricane Isabel (2003)	Forecasting, Methodological Advancement, Planning & Management	Fluvial, Coastal	TRUE	FALSE	FALSE	HEC-RAS	-
Mashriqui et al. 2014	US (Washington DC)	Hurricane Isabel (2003)	Forecasting, Methodological Advancement, Planning & Management	Fluvial, Coastal	TRUE	FALSE	FALSE	HEC-RAS	-
Masina et al. 2015	Italy (Ravenna)	-	Risk Assessment	Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Correlation Coefficients (Kendall’s tau (τ), Pearson’s (r), Spearman’s rho (ρ))
Maskell et al. 2014	UK (England)	Varying return period scenarios	Earth System Processes	Fluvial, Coastal	TRUE	FALSE	FALSE	FVCOM, LISFLOOD-FP	-

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Maymandi et al. 2022	US (Texas, Sabine-Neches Estuary)	Hurricane Rita (2005), Ike (2008), and Harvey (2017)	Earth System Processes	Fluvial, Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, Delft3D	-
Mazas et al. 2014	France (Brest)	Varying return period scenarios	Methodological Advancement, Risk Assessment	Coastal	FALSE	TRUE	FALSE	-	Revised Joint Probability Method (RJPM), Chi-Squared Test (χ2), Peak-over-Threshold (POT)
McGuigan et al. 2015	Canada (Nova Scotia, Bridgewater, LaHave River Estuary)	Varying return period scenarios	Methodological Advancement, Risk Assessment	Fluvial, Coastal	TRUE	FALSE	FALSE	MIKE21	Joint Probability Method (JPM), Extreme Value Analysis
McInnes et al. 2002	Australia (Queensland, Gold Coast Broadwater)	Tropical Cyclones (1989 and 1974)	Earth System Processes, Methodological Advancement	Fluvial, Coastal	TRUE	FALSE	FALSE	GCOM2D, RAMS, WAM	-
Meyers et al. 2021	US (Florida)	Hurricane Hermine (2017), 79 Sanitary Sewer Overflow Events (1996 - 2017), Varying climate change scenarios	Risk Assessment	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Logistic Regression Model (LRM), Temporal Analysis
Ming et al. 2022	UK (London, Thames Estuary)	Varying return period scenarios, 27 Flood Scenarios	Risk Assessment	Fluvial, Pluvial, Coastal	TRUE	TRUE	TRUE	HiPIMS	Joint Probability Method (JPM), Copula, Correlation Coefficients (Kendall's tau (τ), Spearman's rho (ρ)), Peak-over-Threshold (POT),
Modrakowski et al. 2022	Netherlands (Odense, Hvidovre, Vejle)	-	Planning & Management, Risk Assessment	Fluvial, Pluvial, Coastal, Soil Moisture	FALSE	FALSE	FALSE	-	-
Moftakhari et al. 2017	US (Philadelphia, Pennsylvania; San Francisco, California; and Washington DC)	Varying climate change scenarios	Earth System Processes, Risk Assessment	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Copula, Kendall's Correlation Coefficient tau (τ), Block Maxima
Moftakhari et al. 2019	US (California, Newport Bay)	-	Methodological Advancement, Risk Assessment	Fluvial, Coastal	TRUE	TRUE	TRUE	BreZo	Joint Probability Method (JPM), Copula, Correlation Coefficients (Kendall's tau (τ), Spearman's rho (ρ))
Mohammadi et al. 2021	US (New Jersey, Delaware River)	-	Earth System Processes, Risk Assessment	Fluvial, Pluvial, Coastal	FALSE	TRUE	FALSE	-	Copula, Bayesian Network (BN), Storm Surge Statistical Emulator (Kriging/Gaussian Process Regression (GPR)
Mohanty et al. 2022	India (Mumbai, Odisha, Chennai)	Varying return period scenarios	Methodological Advancement	Pluvial, Coastal	TRUE	TRUE	TRUE	MIKE11, MIKE21	Tide-Rainfall Flood Quotient (TRFQ)
Muñoz et al. 2020	US (Georgia, Savannah, Savannah River Delta)	Hurricane Matthew (2016), Varying return period scenarios	Earth System Processes	Fluvial, Coastal	TRUE	TRUE	TRUE	Delft3D-FM	Spatial Analysis, Copula, Multi-hazard Scenario Analysis Toolbox (MhAST), Correlation Coefficients (Kendall's tau (τ), Spearman's rho (ρ))
Muñoz et al. 2021	US (Southeast Coast; Savannah River Estuary, Florida, Georgia, South Carolina, and North Carolina)	Hurricane Matthew (2016)	Methodological Advancement	Fluvial, Coastal	TRUE	TRUE	TRUE	Delft3D-FM	Machine Learning (Convolutional Neural Network (CNN)), Data Fusion (DF)
Muñoz et al. 2022a	US (Alabama, Mobile Bay)	Varying climate change scenarios	Earth System Processes, Planning & Management, Risk Assessment	Fluvial, Pluvial, Coastal	TRUE	TRUE	TRUE	Delft3D-FM	Joint Probability Method (JPM), Copula, Multi-hazard Scenario Analysis Toolbox (MhAST), Peak-over-Threshold (POT)

Author	Geographic Region	Scenario / Event	Application	Compound Drivers	Numerical	Statistical	Numerical & Statistical	Numerical Models	Statistical Methods / Tools
Muñoz et al. 2022b	US (Texas, Galveston Bay; Delaware, Delaware Bay)	Hurricane Harvey (2017), Hurricane Sandy (2012)	Methodological Advancement	Fluvial, Pluvial, Coastal	TRUE	TRUE	TRUE	Delft3D-FM	Bayesian Data Assimilation (DA), Ensemble Kalman Filter (EnKF)
Myers 1970	US (New Jersey, Atlantic City, Long Beach Island)	-	Methodological Advancement, Risk Assessment	Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Frequency Analysis
Najafi et al. 2021	Saint Lucia	Hurricane Matthew (2016)	Risk Assessment	Fluvial, Pluvial, Coastal	TRUE	TRUE	TRUE	HyMOD, LISFLOOD-FP	Strongest Path Method (SPM) Network Risk Analysis, Risklogik Platform, Monte Carlo Simulation
Naseri and Hummel 2022	US (CONUS)	Varying return period scenarios	Risk Assessment	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Copula, Kendall's Correlation Coefficient tau (τ), Spatial Analysis, Temporal Analysis (Mann-Kendall Test), Markov Chain Monte Carlo (MCMC) Algorithm
Nash et al. 2018	Ireland (Cork City)	November 2009 Flood	Earth System Processes	Fluvial, Coastal	TRUE	FALSE	FALSE	MSN_Flood, POM	-
Nasr et al. 2021	US (CONUS)	-	Earth System Processes, Methodological Advancement	Fluvial, Pluvial, Coastal	FALSE	TRUE	FALSE	-	Temporal Analysis, Spatial Analysis, Kendall's Correlation Coefficient tau (τ), Tail Dependence Measure chi (χ), Bootstrap Method
Olabarrieta et al. 2012	US (Gulf and East Coast)	Hurricane Ida (2009) and Nor'Ida	Methodological Advancement	Coastal	TRUE	FALSE	FALSE	COAWST	-
Olbert et al. 2013	Ireland	48 Storm Events (1959-2005), Varying return period scenarios	Earth System Processes, Risk Assessment	Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM)
Olbert et al. 2017	Ireland (Cork City)	2009 Flood Event	Methodological Advancement, Risk Assessment	Fluvial, Pluvial, Coastal	TRUE	FALSE	FALSE	MSN_Flood, POM	-
Orton et al. 2012	US (New York)	-	Methodological Advancement	Fluvial, Pluvial, Coastal	TRUE	FALSE	FALSE	sECOM, WRF	-
Orton et al. 2015	US (New York)	533 Synthetic Tropical Cyclones, 76 Flood Events	Risk Assessment	Fluvial, Coastal	TRUE	TRUE	TRUE	sECOM, SELFE	Bayesian Simultaneous Quantile Regression, Markov Chain Monte Carlo (MCMC) Algorithm
Orton et al. 2016	US (New York, New York Harbor)	Hurricane Irene (2011), Northeaster Storm (2010), 42 Storm Events (1950-2013), Varying return period scenarios	Risk Assessment	Coastal	TRUE	TRUE	TRUE	NYHOPS, sECOM, Holland Wind Model	Hall Stochastic TC Life Cycle Model (Hall and Jewson 2007; Hall and Yonekura 2013), Extreme Value Analysis, Markov Chain Monte Carlo (MCMC) Algorithm, Bootstrap Method
Orton et al. 2018	US (New York, Hudson River)	76 Storm Events (1900–2010)	Risk Assessment	Fluvial, Coastal	TRUE	TRUE	TRUE	sECOM	Hall Stochastic TC Life Cycle Model, Bayesian Simultaneous Quantile Regression, Extreme Value Analysis
Pandey et al. 2021	India (Mahanadi River)	Cyclone Odisha (1999) and Phailin (2013)	Earth System Processes, Methodological Advancement	Fluvial, Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, HEC-RAS	-
Paprotny et al. 2020	Europe (Northwest)	-	Earth System Processes	Fluvial, Pluvial, Coastal	TRUE	TRUE	TRUE	EFAS, Delft3D, LISFLOOD-FP	Tail Dependence Coefficient (λ), Correlation Coefficients (Kendall's tau (τ), Spearman's rho (ρ)), Peak-over-Threshold (POT)

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Park et al. 2011	South Korea	Typhoon Meami (2003)	Forecasting, Planning & Management	Pluvial, Coastal	TRUE	FALSE	FALSE	Holland Wind Model, Hydrodynamic Model (MATLAB)	-
Pasquier et al. 2019	UK (East Coast)	Varying climate change scenarios, Varying return period scenarios	Earth System Processes, Risk Assessment	Fluvial, Pluvial, Coastal	TRUE	FALSE	FALSE	HEC-RAS	Extreme Value Analysis, Peak-over-Threshold (POT)
Peña et al. 2022	US (Florida, Arch Creek Basin)	-	Earth System Processes, Methodological Advancement, Risk Assessment	Fluvial, Pluvial, Coastal, Groundwater	TRUE	FALSE	FALSE	FLO-2D, MODFLOW-2005	-
Petroliagkis et al. 2016	Europe	-	Earth System Processes	Fluvial, Coastal	TRUE	TRUE	TRUE	Delft3D-Flow, ECWAM, LISFLOOD,	Joint Probability Method (JPM), Tail Dependence Measure chi (χ), Peak-over-Threshold (POT)
Petroliagkis et al. 2018	Europe (Rhine River)	Top 80 Compound Events at 32 Rivers Each	Earth System Processes	Coastal	FALSE	TRUE	FALSE	Delft3D-FLOW, ECWAM	Joint Probability Method (JPM), Tail Dependence Measure chi (χ), Peak-over-Threshold (POT)
Phillips et al. 2022	US (Southeast Coast; Florida, Georgia, and South Carolina)	-	Earth System Processes	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Copula, Locally Weighted Scatterplot Smoothing (LOWESS) Autoregressive Moving Average (ARMA) Model
Piecuch et al. 2022	US (West Coast; California, Oregon, and Washington)	Atmospheric Rivers Events (1980-2016)	Earth System Processes	Coastal	FALSE	TRUE	FALSE	-	Temporal Analysis, Regression Analysis, Peak-over-Threshold (POT), Bootstrap Method
Pietrafesa et al. 2019	US (North Carolina)	Hurricanes Dennis and Floyd (1999)	Earth System Processes, Methodological Advancement	Pluvial, Coastal	TRUE	FALSE	FALSE	POM	-
Poulos et al. 2022	Greece (Thrace, Evros River Delta)	8 Flood Events (2005–2018)	Earth System Processes, Risk Assessment	Fluvial, Pluvial	FALSE	TRUE	FALSE	-	Temporal Analysis, Spatial Analysis, Spearman’s Correlation Coefficient rho (ρ)
Prandle and Wolf 1978	UK (East Coast, North Sea, River Thames)	-	Earth System Processes	Coastal	TRUE	FALSE	FALSE	1D Hydrodynamic Model (Prandle 1975)	-
Preisser et al. 2022	US (Texas, Austin)	2015 Memorial Day Flood	Impact Assessment, Risk Assessment	Fluvial, Pluvial	TRUE	TRUE	TRUE	GeoFlood, GeoNet, ProMaIDes	Index Analysis (Social Vulnerability Index (SVI)), Principal Component Analysis (PCA), Spatial Analysis
Qiang et al. 2021	Hong Kong (Tseung Kwan O Town Centre)	Typhoon Mangkhut (2018)	Risk Assessment	Pluvial, Coastal	TRUE	FALSE	FALSE	FLO-2D, SWMM	-
Qiu et al. 2022	China (Guangdong, Pearl River Delta)	76 Tropical Cyclone Events (1957-2018), Varying climate change scenarios	Earth System Processes	Fluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC	-
Quagliolo et al. 2021	Italy (Liguria)	-	Methodological Advancement, Risk Assessment	Pluvial, Coastal	TRUE	FALSE	FALSE	InVEST-UFRM	-
Rahimi et al. 2020	US (California, Oakland Flatlands)	-	Methodological Advancement, Risk Assessment	Pluvial, Coastal, Groundwater	TRUE	FALSE	FALSE	HEC-RAS	-
Ray et al. 2011	US (Texas, Galveston Bay)	Hurricane Ike (2008)	Earth System Processes	Pluvial, Coastal	TRUE	FALSE	FALSE	HEC-HMS, HEC-RAS	-

Author	Geographic Region	Scenario / Event	Application	Compound Drivers	Numerical	Statistical	Numerical & Statistical	Numerical Models	Statistical Methods / Tools
Razmi et al. 2022	US (New York, New York City)	Hurricane Sandy (2012), Hurricane Irene (2011), Varying return period scenarios	Earth System Processes, Methodological Advancement	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Kendall's Correlation Coefficient tau (τ), Temporal Analysis (Mann-Kendall Test)
Ridder et al. 2018	Netherlands	-	Earth System Processes	Pluvial, Coastal	TRUE	FALSE	FALSE	WAQUA	-
Ridder et al. 2020	Global	27 Hazard Pairs (1980–2014), Spatial analysis	Earth System Processes	Pluvial, Coastal, Drought, Soil Moisture	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Spatial Analysis, Likelihood Multiplication Factor (LMF)
Robins et al. 2011	UK (Dyfi Estuary)	Varying climate change scenarios	Earth System Processes, Planning & Management	Pluvial, Coastal	TRUE	FALSE	FALSE	TELEMAC	-
Robins et al. 2021	UK (Humber and Dyfi Estuaries)	56 Flood Events	Earth System Processes	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Linear Regression, Temporal Analysis, Cross-correlation Analysis, Correlation Coefficients (Kendall's tau (τ), Spearman's rho (ρ)), Chi-Squared Test (χ2)
Rodríguez et al. 1999	Spain (Northwest Coast)	-	Risk Assessment	Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM)
Rossiter 1961	UK (Thames Estuary)	-	Earth System Processes	Coastal	TRUE	FALSE	FALSE	1D Hydrodynamic Model	-
Rueda et al. 2016	Spain (Santander)	-	Earth System Processes	Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Climate-based Extremal Index (Θ), Extreme Value Analysis, Monte Carlo Simulation
Ruggiero et al. 2019	US (Washington, Grays Harbor)	Varying climate change scenarios, Varying return period scenarios	Planning & Management, Risk Assessment	Fluvial, Coastal	TRUE	TRUE	TRUE	ADCIRC, HEC-RAS, SWAN	Managing Uncertainty in Complex Models (MUCM) Hydrodynamic Emulator, Temporal Analysis
Sadegh et al. 2018	US (Washington DC, Potomac River)	Varying return period scenarios	Methodological Advancement, Risk Assessment	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Copula, Correlation Coefficients (Kendall's tau (τ), Pearson's (r), Spearman's rho (ρ)), Block Maxima
Saharia et al. 2021	US (New York, Buffalo River & Lake Erie)	Varying return period scenarios	Earth System Processes, Risk Assessment	Fluvial, Coastal	TRUE	TRUE	TRUE	HEC-RAS	Joint Probability Method (JPM), Copula, Kendall's Correlation Coefficient tau (τ)
Saleh et al. 2017	US (New Jersey, Newark Bay)	Hurricane Irene (2011) and Sandy (2012)	Forecasting	Pluvial, Coastal	TRUE	FALSE	FALSE	HEC-HMS, HEC-RAS, sECOM, NYHOPS	-
Sampurno et al. 2022a	Indonesia (Pontianak, Kapuas River Delta)	December 2018 Flood Event	Forecasting, Methodological Advancement	Fluvial, Pluvial, Coastal	TRUE	TRUE	TRUE	SLIM, SWAT	Machine Learning (Random Forest (RF), Multiple Linear Regression (MLR), Support Vector Machine (SVM))
Sampurno et al. 2022b	Indonesia (Pontianak, Kapuas River Delta)	-	Earth System Processes	Fluvial, Coastal	TRUE	FALSE	FALSE	SLIM	-
Samuels and Burt 2002	UK (Wales, Pontypridd, Taff River, Ely River)	Varying return period scenarios, Varying climate change scenarios	Planning & Management, Risk Assessment	Fluvial, Coastal	TRUE	TRUE	TRUE	Flood Modeller/ISIS	Joint Probability Method (JPM), JOIN-SEA Model, Monte Carlo Simulation
Sangsefidi et al. 2022	US (California, Imperial Beach)	-	Risk Assessment	Pluvial, Coastal, Groundwater	TRUE	FALSE	FALSE	PCSWMM	-

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Santiago-Collazo et al. 2021	US (Mississippi, Mississippi River Delta)	-	Earth System Processes, Risk Assessment	Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC	-
Santos et al. 2017	UK	92 Extreme Wave Events (2002-2016), Varying return period scenarios	Earth System Processes	Coastal	FALSE	TRUE	FALSE	-	Spatial Analysis, Temporal Analysis, Extreme Value Analysis, Kendall's Correlation tau (τ), Peak-over-Threshold (POT)
Santos et al. 2021a	US (Texas, Sabine Lake)	-	Earth System Processes, Methodological Advancement, Risk Assessment	Fluvial, Pluvial, Coastal	FALSE	TRUE	FALSE	-	Copula, Multiple Linear Regression (MLR), Extreme Value Analysis, Kendall's Correlation tau (τ), Peak-over-Threshold (POT)
Santos et al. 2021b	Netherlands	Varying return period scenarios	Earth System Processes, Methodological Advancement	Pluvial, Coastal	TRUE	TRUE	TRUE	RTC-Tools	Joint Probability Method (JPM), Copula, Machine Learning (Artificial Neural Network (ANN), Multiple Linear Regression (MLR), Random Forest (RF)), Kendall's Correlation Coefficient tau (τ), Block Maxima
Serafin and Ruggiero 2014	US (Oregon)	Varying return period scenarios	Earth System Processes, Risk Assessment	Coastal	FALSE	TRUE	FALSE	-	Total Water Level Full Simulation Model (TWL-FSM), Temporal Analysis (Declustering), Extreme Value Analysis, Monte Carlo Simulation, Peak-over-Threshold (POT)
Serafin et al. 2019	US (Washington)	Varying return period scenarios	Earth System Processes	Fluvial, Coastal	TRUE	TRUE	TRUE	ADCIRC, HEC-RAS, SWAN	Total Water Level Full Simulation Model (TWL-FSM), Extreme Value Analysis, Temporal Analysis, Spatial Analysis, Monte Carlo Simulation
Shahapure et al. 2010	India (Maharashtra, Navi Mumbai)	5 Rainfall Events	Methodological Advancement	Pluvial, Coastal	TRUE	FALSE	FALSE	1D Hydrodynamic Model (GIS-based)	-
Shen et al. 2019	US (Virginia, Norfolk)	Varying return period scenarios	Planning & Management, Risk Assessment	Pluvial, Coastal	TRUE	FALSE	FALSE	ESTRY, TUFLOW	Transition Zone Index (TZI), Spatial Analysis, Temporal Analysis
Shen et al. 2022	US (Virginia, Norfolk)	Varying return period scenarios, Varying climate change scenarios	Impact Assessment	Pluvial, Coastal	TRUE	TRUE	TRUE	CORDEX, Delft3D, TUFLOW	Extreme Value Analysis, Total Link Close Time (TLC) Index
Sheng et al. 2022	US (Florida)	Varying Tropical Cyclone events, Varying climate change scenarios, Varying return period scenarios	Earth System Processes, Risk Assessment	Pluvial, Coastal	TRUE	TRUE	TRUE	ADCIRC, CAM, CESM, CH3D, HiRAM, RFMS, SWAN	Joint Probability Method with Optimal Sampling (JPM-OS), Monte Carlo Life-Cycle (MCLC) Simulation, Peak-over-Threshold (POT)
Shi et al. 2022	China (Zhejiang, Xiangshan)	Typhoons Haikui (2012) and Fitow (2013)	Earth System Processes, Planning & Management	Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, SWMM	-
Silva-Araya et al. 2018	US (Puerto Rico)	Hurricane Georges (1998)	Methodological Advancement	Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, GSSHA, SWAN	-
Skinner et al. 2015	UK (Humber Estuary)	2013 Storm Event	Methodological Advancement, Risk Assessment	Coastal	TRUE	FALSE	FALSE	CAESAR-LISFLOOD, LISFLOOD-FP	-
Sopelana et al. 2018	Spain (Betanzos)	40 Flood Events	Methodological Advancement	Fluvial, Coastal	TRUE	FALSE	FALSE	Iber	-

Author	Geographic Region	Scenario / Event	Application	Compound Drivers	Numerical	Statistical	Numerical & Statistical	Numerical Models	Statistical Methods / Tools
Stamey et al. 2007	US (Maryland and Virginia)	Hurricane Isabel (2003), Tropical Storm Ernesto (2006), and 2006 Nor'easter Storm	Forecasting, Planning & Management	Fluvial, Coastal	TRUE	FALSE	FALSE	AHPS, ELCIRC, RAMS, ROMS, UnTRIM, WRF	-
Steinschneider 2021	Canada (Ontario, Lake Ontario)	-	Earth System Processes, Risk Assessment	Coastal	TRUE	TRUE	TRUE	LOOFS	Bayesian Hierarchical Model, Monte Carlo Simulation, Spatial Analysis, Chi-Squared Test (χ2)
Stephens and Wu 2022	New Zealand	-	Earth System Processes	Fluvial, Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Kendall’s Correlation Coefficient tau (τ), Spatial Analysis, Temporal Analysis, Peak-over-Threshold (POT)
Stephens et al. 2022	US (Texas, Galveston Bay)	Hurricane Harvey (2017)	Methodological Advancement	Fluvial, Pluvial, Coastal	TRUE	FALSE	FALSE	AdH	-
Svensson and Jones 2002	UK (East Coast)	-	Earth System Processes	Fluvial, Pluvial, Coastal	FALSE	TRUE	FALSE	-	Dependence Measure chi (χ), Temporal Analysis, Spatial Analysis, Peak-over-Threshold (POT), Bootstrap Method
Svensson and Jones 2004	UK (South and West Coast)	-	Earth System Processes	Fluvial, Pluvial, Coastal	FALSE	TRUE	FALSE	-	Dependence Measure chi (χ), Temporal Analysis, Spatial Analysis, Peak-over-Threshold (POT), Bootstrap Method
Tahvildari et al. 2022	US (Virginia)	Hurricane Irene (2011)	Planning & Management	Pluvial, Coastal	TRUE	TRUE	TRUE	Delft3D-FLOW, TUFLOW	Spatial Analysis (Traffic Network Analysis)
Tanim and Goharian 2021	Bangladesh (Chittagong)	-	Earth System Processes, Methodological Advancement	Pluvial, Coastal	TRUE	TRUE	TRUE	Delft3D-FLOW, SWAN, SWMM	Joint Probability Method (JPM), Copula, Spearman's Correlation Coefficient rho (ρ), Spatial Analysis, Temporal Analysis
Tanir et al. 2021	US (Washington DC, Potomac River)	-	Impact Assessment, Risk Assessment	Fluvial, Pluvial, Coastal	TRUE	TRUE	TRUE	HEC-RAS	Socio-Economic Vulnerability Index (SOVI), Exposure Index (EI), Flood Socio-Economic Vulnerability Index (FSOVI), HAZUS-MH Damage Assessment Tool, Principal Component Analysis (PCA), Spatial Analysis
Tao et al. 2022	China (Wuhan, Yangtze River)	Compound Events (1980 -2020)	Earth System Processes, Risk Assessment	Fluvial, Pluvial	FALSE	TRUE	FALSE	-	Compound Intensity Index (CII), Joint Probability Method (JPM), Copula, Multivariate Copula Analysis Toolbox (MvCAT), Correlation Coefficients (Kendall’s tau (τ), Pearson's (r), Spearman's rho (ρ)), Temporal Analysis (Mann-Kendall Test)
Tawn 1992	UK	-	Methodological Advancement, Risk Assessment	Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Revised Joint Probability Method (RJPM), Extreme Value Analysis
Tehranirad et al. 2020	US (California, San Francisco Bay)	February 2019 Storm Event	Forecasting, Planning & Management	Fluvial, Pluvial	TRUE	FALSE	FALSE	Hydro-CoSMoS	-
Thompson and Frazier, 2014	US (Florida, Sarasota County)	Varying climate change scenarios	Methodological Advancement, Risk Assessment	Pluvial, Coastal	TRUE	TRUE	TRUE	ICPR, SLOSH	Spatial Analysis (Geographic Weighted Regression (GWR), Moran’s I, Linear Probability Model (LPM))
Torres et al. 2015	US (Texas, Galveston Bay)	Hurricane Katrina (2005), Ike (2008), and Isaac (2012)	Earth System Processes, Planning & Management	Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, HEC-RAS, SWAN, Vflo	-

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Tromble et al. 2010	US (North Carolina, Tar and Neuse River)	Tropical Storm Alberto (2006)	Methodological Advancement	Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, HL-RDHM, Vflo	-
Tu et al. 2018	China (Xixiang Basin)	-	Risk Assessment	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Kendall's Correlation Coefficient tau (τ), Block Maxima, Peak-over-Threshold (POT)
Valle-Levinson et al. 2020	US (Texas, Houston, Galveston Bay)	Hurricane Harvey (2017)	Earth System Processes	Pluvial, Coastal	TRUE	TRUE	TRUE	ROMS	Flow Interaction Ratio Index (μ), Temporal Analysis
Van Berchum et al. 2020	Mozambique (Beira)	-	Risk Assessment	Pluvial, Coastal	TRUE	FALSE	FALSE	FLORES	-
Van Cooten et al. 2011	US (North Carolina)	Hurricane Isabelle (2003), Earl (2010) and Irene (2011), Tropical Storm Nicole (2010)	Forecasting, Methodological Advancement	Fluvial, Pluvial, Coastal	TRUE	FALSE	FALSE	ADCIRC, CI-FLOW, HL-RDHM, RUC	-
Van Den Hurk et al. 2015	Netherlands	January 2012 Near Flood	Risk Assessment	Pluvial, Coastal	FALSE	TRUE	FALSE	EC-Earth, RACMO2, RTC-Tools	Joint Probability Method (JPM), Spatial Analysis, Temporal Analysis
Vitousek et al. 2017	Global	Varying climate change scenarios	Earth System Processes, Risk Assessment	Coastal	FALSE	TRUE	FALSE	-	Extreme Value Analysis, Monte Carlo Simulation
Vongvisessomjai and Rojanakamthorn 1989	Thailand (Chao Phraya River)	-	Earth System Processes	Fluvial, Coastal	TRUE	TRUE	TRUE	1D Hydrodynamic Model	Analytical Perturbation Method, Harmonic Analysis, Temporal Analysis
Wadey et al. 2015	UK (Sefton and Suffolk)	Cyclone Xaver (2013), Varying return period scenarios	Earth System Processes, Risk Assessment	Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Temporal Analysis (Clustering)
Wahl et al. 2015	US (CONUS)	-	Earth System Processes, Risk Assessment	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Temporal Analysis, Kendall's Correlation Coefficient tau (τ)
Walden et al. 1982	UK (South Coast)	-	Earth System Processes, Methodological Advancement	Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Temporal Analysis
Wang et al. 2014	US (New York, New York City)	Hurricane Sandy (2012)	Methodological Advancement	Coastal	TRUE	FALSE	FALSE	SELFE, RAMS, UnTRIM	-
Wang et al. 2015	US (Washington DC, Potomac River)	Hurricane Isabel (2003)	Methodological Advancement	Fluvial, Coastal	TRUE	FALSE	FALSE	UnTRIM	-
Wang et al. 2021	Canada (Newfoundland and Labrador)	Varying return period scenarios, Varying climate change scenarios	Earth System Processes, Risk Assessment	Fluvial, Coastal	TRUE	FALSE	FALSE	HEC-HMS, HEC-RAS, WRF	-
Ward et al. 2018	Global	-	Earth System Processes	Fluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Kendall's Correlation Coefficient tau (τ), Spatial Analysis, Block Maxima, Peak-over-Threshold (POT)
Webster et al. 2014	Canada (Nova Scotia, Bridgewater, LaHave River Estuary)	Varying climate change scenarios, Varying return period scenarios	Risk Assessment	Fluvial, Coastal	TRUE	TRUE	TRUE	MIKE11, MIKE21	Joint Probability Method (JPM), Extreme Value Analysis

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White 2007	UK (East Sussex, Lewes, Ouse River)	October 2000 Flood Event	Earth System Processes, Methodological Advancement, Risk Assessment	Fluvial, Coastal	TRUE	TRUE	TRUE	-	Joint Probability Method (JPM), Dependence Measure chi (χ), Block Maxima, Peak-over-Threshold (POT)
Williams et al. 2016	Europe (UK, US, Netherlands, and Ireland)	-	Earth System Processes	Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Kendall's Correlation Coefficient tau (τ), Temporal Analysis
Wolf 2009	Myanmar (Irrawaddy River Delta)	May 2008 Flood Event	Earth System Processes	Coastal	TRUE	FALSE	FALSE	ADCIRC, SWAN	-
Wu and Leonard 2019	Australia	-	Earth System Processes	Pluvial, Coastal	TRUE	TRUE	TRUE	ROMS	Joint Probability Method (JPM), Kendall’s Correlation tau (τ), Spatial Analysis, Peak-over-Threshold (POT)
Wu et al. 2018	Australia	-	Earth System Processes	Pluvial, Coastal	TRUE	TRUE	TRUE	ROMS	Extreme Value Analysis, Temporal Analysis, Spatial Analysis, Pearson's Correlation Coefficient (r), Peak-over-Threshold (POT)
Wu et al. 2021	Australia (Swan River)	Varying return period scenarios	Methodological Advancement, Risk Assessment	Fluvial, Pluvial, Coastal	TRUE	TRUE	TRUE	MIKE21	Joint Probability Method (JPM), Frequency Analysis, Peak-over-Threshold (POT)
Xiao et al. 2021	US (Delaware, Delaware Bay)	Hurricane Irene (2011), Isabel (2003), Sandy (2012); and Tropical Storm Lee (2011)	Earth System Processes	Fluvial, Coastal	TRUE	TRUE	TRUE	FVCOM	Temporal Analysis (Complex Demodulation, Singular Spectral Analysis (SSA))
Xu et al. 2014	China (Fuzhou City)	-	Risk Assessment	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Temporal Analysis (Mann-Kendall U Test, Pettitt Test)
Xu et al. 2019	China (Haikou City)	-	Risk Assessment	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula
Xu et al. 2022	China (Shanghai)	Tropical Cyclones and Peak Water Level Events (1961-2018)	Risk Assessment	Pluvial, Coastal	TRUE	TRUE	TRUE	D-Flow FM	Copula, Correlation Coefficients (Kendall’s tau (τ), Spearman’s rho (ρ))
Xu et al. 2022	China (Hainan, Haikou)	-	Earth System Processes, Risk Assessment	Pluvial, Coastal	TRUE	TRUE	TRUE	PCSWMM	Joint Probability Method (JPM), Copula, Monte Carlo Simulation, Kendall’s Correlation Coefficient tau (τ)
Yang and Qian 2019	China (Shenzhen, Pearl River)	-	Earth System Processes, Methodological Advancement	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Particle Swarm Optimization (PSO)
Yang et al. 2020	China (Jiangsu Province, Lianyungang, Yancheng and Nantong)	-	Earth System Processes	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Particle Swarm Optimization (PSO)
Yang et al. 2021	China (Shanghai, Qianbujing Creek)	Typhoon Fitow (2013), October 8 Levee Breach	Earth System Processes, Methodological Advancement	Fluvial, Pluvial, Coastal, Damming/ Dam Failure	TRUE	FALSE	FALSE	FloodMap	-
Ye et al. 2020	US (East and Gulf Coast, Deleware Bay)	Hurricane Irene (2011)	Methodological Advancement	Fluvial, Pluvial, Coastal	TRUE	FALSE	FALSE	NWM, SCHISM, 3D Baroclinic Atmospheric Model	-
Ye et al. 2021	US (Southeast Coast, North Carolina & South Carolina)	Hurricane Florence (2018)	Earth System Processes, Methodological Advancement	Fluvial, Pluvial, Coastal	TRUE	FALSE	FALSE	HYCOM, NWM, SCHISM, SMS	-

Author	Geographic Region	Scenario / Event	Application	Compound Drivers	Numerical	Statistical	Numerical & Statistical	Numerical Models	Statistical Methods / Tools
Yeh et al. 2006	Taiwan (Longdong, Hualien, Chiku, and Eluanbi)	30 Typhoon Events (2001-2005), Varying return period scenarios	Risk Assessment	Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Frequency Analysis
Zahura and Goodall 2022	US (Virginia, Norfolk)	-	Methodological Advancement	Pluvial, Coastal, Soil Moisture	TRUE	TRUE	TRUE	ESTRY, TUFLOW	Machine Learning (Random Forest (RF)), Topographic Wetness Index (TWI), Depth to Water Index (DTW)
Zellou and Rahali 2019	Morocco (Bouregreg River)	Varying return period scenarios	Risk Assessment	Pluvial, Coastal	TRUE	TRUE	TRUE	CAESAR-LISFLOOD	Joint Probability Method (JPM), Copula, Kendall's Correlation Coefficient tau (τ), Tail Dependence Coefficient (λ)
Zhang and Chen 2022	China	-	Earth System Processes, Risk Assessment	Fluvial, Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Copula, Kendall's Correlation Coefficient tau (τ), Spatial Analysis, Temporal Analysis, Peak-over-Threshold (POT), Block Maxima
Zhang and Najafi 2020	Saint Lucia	Hurricane Mathew (2016)	Risk Assessment	Fluvial, Pluvial, Coastal	TRUE	FALSE	FALSE	HYMOD, LISFLOOD-FP	-
Zhang et al. 2011	US (Alaska, Prince William Sound)	1964 Alaska Tsunami	Earth System Processes	Coastal, Tsunami	TRUE	FALSE	FALSE	SELFE	-
Zhang et al. 2020	US (Delaware, Delaware Bay)	Hurricane Irene (2011)	Earth System Processes, Methodological Advancement	Pluvial, Coastal	TRUE	FALSE	FALSE	SCHISM	-
Zhang et al. 2022	China (Zhejiang, Ling River Basin)	Typhoon Lekima (2019) and Wiph (2007)	Earth System Processes	Fluvial, Pluvial, Coastal	TRUE	FALSE	FALSE	1D/2D Coupled Hydrodynamic Model	-
Zheng et al. 2013	Australia	-	Earth System Processes	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Extreme Value Analysis, Dependence Measure chi (χ), Spatial Analysis, Temporal Analysis, Peak-over-Threshold (POT)
Zheng et al. 2014	Australia (Sydney, Hawkesbury-Nepean Catchment)	-	Earth System Processes, Risk Assessment	Pluvial, Coastal	FALSE	TRUE	FALSE	-	Joint Probability Method (JPM), Extreme Value Analysis, Block Maxima, Peak-over-Threshold (POT)

Table A2. Table of numerical models, frameworks, systems, and toolsets observed in literature database studies for simulating hydrologic, hydrodynamic, oceanographic, and atmospheric systems that contribute to compound flooding.

Model Acronym	**Full Names**	**Model Type**
ADCIRC	Advanced CIRCulation	Hydrodynamic Model
AdH	Adaptive Hydraulics Modeling System	Coupled Hydrodynamic Model System
AHPS	Advanced Hydrologic Prediction Service	Coupled Atmospheric & Hydrological Model System
ASGS	ADCIRC Surge Guidance System	Hydrodynamic Model System
ASGS-STORM	ASGS-Scalable, Terrestrial, Ocean, River, Meteorology	Coupled Model System (ASGS, SWAN, HL-RDHM, DAH, NAM)
AutoRoute	-	Hydrological Model
BreZo	-	Hydrodynamic Model
CAESAR	-	Geomorphic Evolution Hydrological Model
CAM	Community Atmosphere Model	Atmospheric Model
CaMa-Flood	Catchment-based Macro-scale Floodplain	Hydrodynamic Model
CESM	Community Earth System Model	Atmospheric Model
CH3D	Curvilinear-grid Hydrodynamics 3D Model	Hydrodynamic Model
CI-FLOW	Coastal and Inland Flooding Observation and Warning Project	Hydrological Model
CKF	Climate Knowledge Facility System	Coupled Hydrological & Hydrodynamic Model System
CMIP5	Coupled Model Intercomparison Project 5	Coupled Atmospheric and Hydrodynamic Model System/Framework
CMIP6	Coupled Model Intercomparison Project 6	
COAWST	Coupled-Ocean-Atmosphere-Wave-Sediment Transport Modeling System	Coupled Hydrodynamic & Atmospheric Model System (ROMS, SWAN, WaveWatch III, InWave)
CORDEX	Coordinated Regional Climate Downscaling Experiment	Atmospheric Model System
COS-Flow	Coupled Overland-Sewer Flow model	Hydrodynamic Model
CoSMoS	Coastal Storm Modeling System	Coupled Hydrodynamic & Atmospheric Model System
CREST	Coupled Routing and Excess Storage	Hydrological Model
CREST-SVAS	Coupled Routing and Excess Storage-Soil-Vegetation-Atmosphere-Snow	Hydrological Model
D-Flow FM	D-Flow Flexible Mesh	Hydrodynamic Model
DCSM	Dutch Continental Shelf Model	Hydrodynamic Model
Delft3D-FM	Delft 3D Flexible Mesh Suite	Toolset
Delft3D-FLOW	-	Hydrodynamic Model
Delft3D-WAVE	-	Coupled Hydrodynamic Model (Delft3D, SWAN)
Delft-FIAT	Flood Impact Analysis Tool	Toolset
Delft-FLS	DELFT Flooding System	Hydrodynamic Model
EC-Earth	European community Earth System Model	Atmospheric, Hydrological, & Hydrodynamic Model System
ECHAM5	ECMWF Hamburg Model Version 5	Atmospheric Model
ECWAM	ECMWF Ocean Wave Model	Hydrodynamic Model
EFAS	European Flood Awareness System	Hydrological Model
ELCIRC	Eulerian-Lagrangian CIRCulation	Hydrodynamic Model
ESTRY	-	Hydrodynamic Model
ESTOFS	Extra Tropical Storm and Tide Operational Forecast System	Hydrodynamic Model
ETSS	Extratropical Storm Surge model	Hydrodynamic Model
FES2012	Finite Element Solution Model	Hydrodynamic Model
FLO-2D	-	Hydrodynamic Model
FloodMap	-	Hydrological & Hydrodynamic Model

Flood Modeller/ISIS	-	Hydrodynamic Model
FLORES	Flood risk Reduction Evaluation and Screening	Hydrodynamic Model
FLOW-3D	-	Hydrodynamic Model
FVCOM	Finite Volume Community Ocean Model	Hydrodynamic Model
GCOM2D	Global Environmental Modelling Systems (GEMS) 2D Coastal Ocean Model	Hydrodynamic Model
GeoFlood	-	Hydrological Model
GeoNet	-	Toolset
GSSHA	Gridded Surface Subsurface Hydrologic Analysis	Hydrological Model
GTSM	Global Tide and Surge Model	Hydrodynamic Model
H*WIND	Hurricane Wind Analysis System	Atmospheric Model
HADGEM	HADley Centre Global Environment Model	Coupled Atmospheric & Hydrodynamic Model System
HBV	Hydrologiska Byråns Vattenbalansavdelning	Hydrological Model
HEC-HMS	Hydrologic Engineering Centre’s - Hydrologic Modeling System	Hydrological Model
HEC-RAS	Hydrologic Engineering Centre’s - River Analysis System	Hydrological Model
HiPIMS	High-Performance Integrated Hydrodynamic Modelling Software	Hydrological & Hydrodynamic Model
HiRHAM	High Resolution Atmospheric Model	Atmospheric Model
HL-RDHM	Hydrology Laboratory - Research Distributed Hydrologic Model	Hydrological Model
Holland Wind Model	Holland Wind Model	Atmospheric Model
HYCOM	HYbrid Coordinate Ocean Model	Hydrodynamic Model
HydroMT	Hydro Model Tools	Toolset
HyMOD	HYdrological MODel	Hydrological Model
Iber	Iberaula	Hydrodynamic Model
ICRP	Interconnected Channel and Pond Routing Model	Hydrological & Hydrodynamic Model
InVEST-UFRM	Integrated Valuation of Ecosystem Services and Tradeoffs - Urban Flood Risk Mitigation model	Toolset
IOKA	Oceanweather's Interactive Kinematic Objective Analysis System	Atmospheric Model
LISFLOOD-FP	-	Hydrodynamic Model
LOOFS	Lake Ontario Operational Forecast System	Coupled Hydrodynamic Model System (FVCOM, CICE)
MATSIRO-GW	Minimal Advanced Treatments of Surface Integration and RunOff - Groundwater	Hydrological Model
MIKE+	-	Hydrological & Hydrodynamic Model
MIKE11	-	Hydrodynamic Model
MIKE21	-	Hydrodynamic Model
MISDc	Modello Idrologico SemiDistribuito in continuo	Hydrological Model
MODFLOW	Modular Hydrologic Model	Hydrological Model
Mog2D		Hydrodynamic Model
MPI-OM	Max Planck Institute - Ocean/Sea-Ice Model	Hydrodynamic Model
MRI-CGCM2	Meteorological Research Institute coupled General Circulation Model Version 2	Coupled Atmospheric & Hydrodynamic Model
MSN_Flood	-	Hydrodynamic Model
NAM	Nedbor-Afstromnings Model	Hydrological Model
NAM	North American Mesoscale Forecast System	Atmospheric Model
NEMO	Nucleus for European Modelling of the Ocean	Hydrodynamic Model
NWM	National Water Model	Hydrological Model
NYHOPS	New York Harbor Observing and Prediction System	Hydrodynamic Model
ONDA	-	Hydrodynamic Model

PCSWMM	Personal Computer Storm Water Management Model	Hydrological & Hydrodynamic Model
POM	Princeton Ocean Model	Hydrodynamic Model
PQRUT	-	Hydrological Model
ProMaIDes	Protection Measures against Inundation Decision Support	Hydrodynamic Model & Toolset
RACMO2	Regional Atmospheric Climate Model Version 2	Atmospheric Model
RAMS	Regional Atmospheric Modelling System	Atmospheric Model
ReAFFIRM	Real-time Assessment of Flash Flood Impacts Framework	Hydrological Model
RegCM3	Regional Climate Model Version 3	Atmospheric Model
RFMS	Rapid Forecasting and Mapping System	Coupled Hydrodynamic Model System (SLOSH and CH3D)
ROMS	Regional Ocean Modelling System	Hydrodynamic Model
RS3	Rocscience 3D Finite Element Analysis	Toolset
RTC-Tools	-	Hydrological Model & Toolset
RUC	Rapid Update Cycle	Atmospheric Model
SCHISM	Semi-implicit Cross-scale Hydroscience Integrated System Model	Hydrodynamic Model
sECOM	Stevens Estuarine and Coastal Ocean Model	Hydrodynamic Model
SELFE	Semi-Implicit Finite-Element/Volume Eulerian-Lagrangian Algorithm	Hydrodynamic Model
SFAS	Stevens Flood Advisory System	Coupled Hydrologic & Hydrodynamic Model System
SFINCS	Super-Fast Inundation of CoastS	Hydrodynamic Model
SHAWLWV	Model for Simulation of Shallow Water Wave Growth, Propagation, and Decay	Hydrodynamic Model
SIPSON	Simulation of Interaction between Pipe flow and Surface Overland flow in Networks	Hydrodynamic Model
SLIM	Second-generation Louvain-la-Neuve Ice-ocean Model	Hydrodynamic Model
SLOSH	Sea, Lake, and Overland Surges from Hurricanes	Hydrodynamic Model
SMS	Surface-water Modeling System	Toolset
SNAP	Stevens Northwest Atlantic Prediction Model	Hydrodynamic Model
SPHY	Spatial Processes in HYdrology	Hydrological Model
SPLASH	Special Program to List Amplitudes of Surges from Hurricanes	Atmospheric and Hydrodynamic Model System
STWAVE	Steady State Spectral Wave	Hydrodynamic Model
SWAN	Simulating Waves Nearshore	Hydrodynamic Model
SWAT	Soil & Water Assessment Tool	Toolset
SWMM	Storm Water Management Model	Hydrological Model
TELEMAC	TELEMAC-MASCARET	Hydrodynamic Model
TUFLOW	-	Hydrodynamic Model
UIM	Urban Inundation Model	Hydrodynamic Model
UnTRIM	-	Hydrodynamic Model
Vflo	Vieux FLOod	Hydrological Model
WAM	Wave Model	Hydrodynamic Model
WAQUA	WAter movement and water QUAlity modelling	Hydrodynamic Model
WGHM	WaterGAP Global Hydrology Model	Hydrological Model
WIFM	WES Implicit Flooding Model	Hydrodynamic Model
WRF	Weather Research and Forecast Model	Atmospheric Model
WW3/WaveWatch III	WAVE-height, WATer depth and Current Hindcasting Version 3	Hydrodynamic Model Framework
XPSWMM	XP Solutions Storm Water Management Model	Hydrological & Hydrodynamic Model