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Review

Modelling and Mapping Rapid-Onset Coastal Flooding: A Systematic Literature Review

Alice Re [1,*], Lorenzo Minola [1,2,3] and Alessandro Pezzoli [1]

[1] Interuniversity Department of Regional and Urban Studies and Planning (DIST), Politecnico and University of Turin, 10125 Turin, Italy; lorenzo.minola@gmail.com (L.M.); alessandro.pezzoli@polito.it (A.P.)
[2] Regional Climate Group, Department of Earth Sciences, University of Gothenburg, 405 30 Gothenburg, Sweden
[3] Centro de Investigaciones Sobre Desertificación, Consejo Superior de Investigaciones Científicas (CIDE, CSIC-UV-Generalitat Valenciana), Climate, Atmosphere and Ocean Laboratory (Climatoc-Lab), 46113 Moncada, Valencia, Spain
* Correspondence: alice.re@polito.it

Abstract: Increases in the magnitude and frequency of extreme flood events are among the most impactful consequences of climate change. Coastal areas can potentially be affected by interactions among different flood drivers at the interface of terrestrial and marine ecosystems. At the same time, socio-economic processes of population growth and urbanization can lead to increases in local vulnerability to climate extremes in coastal areas. Within this context, research focusing on modelling and mapping rapid-onset coastal flooding is essential (a) to support flood risk management, (b) to design local climate adaptation policies and (c) to increase climate resilience of coastal communities. This systematic literature review delineates the state-of-the art of research on rapid-onset coastal flooding. It provides a comprehensive picture of the broad range of methodologies utilised to model flooding and highlights the commonly identified issues, both from a scientific standpoint and in terms of the policy implications of translating research outputs into actionable information. As flood maps represent fundamental instruments in the communication of research outcomes to support decision making and increase climate resilience, a focus on the spatial representation of coastal floods proposed in the literature is adopted in this review.

Keywords: coastal flooding; sea level rise; climate change; flood modeling; flood mapping

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1. Introduction

Coastal areas are particularly susceptible to climate change-related extreme events because of their location at the intersection between marine and land systems, which makes them susceptible to being affected by a combination of fluvial, pluvial and coastal flood drivers [1]. In light of these factors, increasing information is needed to support flood disaster prevention and coastal risk management, and considerable research addressing coastal flooding has been developed in recent times in numerous disciplinary fields [2,3].

Maps are one of the most commonly produced outputs of coastal flood modelling, as they represent important instruments for understanding and communicating complex flooding processes. The role of maps for conveying information and supporting decision making is crucial especially for the communication of climate-related risks in densely populated urban environments, where the multifaceted components of risk and their interactions must be jointly represented [4].

Preventive modelling and mapping applications are especially relevant in the context of disaster prevention, as often climate-related hazards have never been observed before for a given area. To that extent, the simulation of design flood events and the identification of areas potentially affected by coastal floods for different climate change scenarios are crucial.

Within this context, the objective of this systematic literature review is to delineate in a systematic way the extensive scientific research on modelling and mapping rapid-onset floods in coastal areas, focusing on preventive flood assessments because of their role in supporting coastal planning, adaptation policies and flood risk management strategies. It aims to identify the most relevant research gaps in the field, to assess the strengths and drawbacks of the considered individual methodologies, and to highlight the peculiarities resulting from mapping flooding specifically in coastal areas. This review further aims to highlight how different methodologies are used to describe variable configurations of the individual components of the coastal flood system, including the drivers and sources of flooding in coastal areas, the water–land coastal interface, the disaster-receiving body, the consequences of flooding and their complex interactions. Within this framework, a dedicated focus is placed on the disaster-receiving body, thus analyzing the spatial development of floods on emergent portions of coastal areas.

By examining a broad research spectrum, this work further allows for capturing the state-of-the-art of proposed risk mitigation and coastal adaptation strategies, and contributes by highlighting the role of flood research in supporting policymaking as envisioned by the scientific community.

Some overlap exists between the scope of this work and that of some previously published review articles. However, previous studies adopted either an exclusive focus on coastal flood mapping through a narrow set of methodologies, or focused on a wider array of methodologies to map other types of floods—mostly pluvial or fluvial [5,6]. Within the former class of publications, Ferreira et al. [7] analysed process-based indicators for sandy coasts subject to storm-induced hazards. Thorough reviews on numerical modelling of coastal flooding were proposed by Gallien et al. [8] and Santiago-Collazo et al. [9], who investigated, respectively, the modelling of wave overtopping in defended urban backshores and the integration of numerical models describing different flood drivers for compound coastal flood modelling. Among the second type of works identified, Mudashiru et al. [10,11] reviewed flood hazard and susceptibility mapping with a comprehensive approach in terms of the methodologies considered but without a specific focus on coastal flooding. Avila-Aceves et al. [2] analysed the geospatial modelling of pluvial and fluvial flooding, highlighting the wide array of methodologies utilised to study floods in general (including hydrologic/hydraulic modelling, GIS-based Multi Criteria Decision Analysis (MCDA) and Machine Learning (ML)). Bentivoglio et al. [6] reviewed Deep Learning (DL) methodologies for flood mapping for a variety of flood drivers, considering both preventive and post-event flood mapping. In the introduction of a book contribution, Batista [12] adopted a perspective similar to the one proposed in this work and analysed within a general outlook the methodologies utilised in the literature for coastal flood hazard mapping, providing a base for the analysis which could be further expanded and systematised. A more extensive effort was presented by Vousdoukas et al. [13], who investigated large-scale coastal flood hazard mapping due to extreme marine events through a wide series of approaches—including simplified models, semi-dynamic models, dynamic models and the flood intensity index approach.

To the best of the authors' knowledge, at the time of writing, this work is the first to propose a comprehensive and systematic picture of the state-of-the-art of all available methodologies used for pre-event coastal flood modelling and mapping. Because of the broad scope adopted in terms of methodologies considered, this systematic literature review might be further characterised as a systematic scoping review [14,15].

The remainder of this article is organised as follows. The systematic protocol utilised to develop this review is laid out in Section 2. In Section 3, the review results are presented mirroring the various components of the coastal flood system. Section 4 outlines the methodological state-of-the-art of coastal flood modelling. The different types of coastal flood maps proposed are analysed in Section 5. Section 6 addresses the policy implications of the reviewed literature. Discussion is provided and conclusions are drawn in Section 7.

2. Systematic Review Protocol

This study was carried out following a systematic review protocol based on the Joanna Briggs Institute (JBI) guidelines for scoping reviews [16] in order to define *a priori* the objectives, methods and reporting of the review. The adopted workflow was composed of a data identification phase, a screening phase and a full-text examination phase as detailed in Figure 1. All phases were informed by the criteria for article inclusion summarised in Table 1 and detailed in Sections 2.1 and 2.2.

Table 1. Inclusion and exclusion criteria utilised for selection of articles.

Criterion	DSPRC/PICOC Component	Explanation
Climate criterion	Driver	The article must not focus exclusively on climate variation, time series or extreme value analysis, or the development of climate scenarios or projections.
Multi-hazard criterion	Driver/Source	The article must not focus exclusively on multi-hazard assessment.
Hazard criterion	Source	The article must not focus exclusively on long-term SLR, pluvial-only or fluvial-only floods in coastal areas.
Oceanography criterion	Source	The article must not focus exclusively on water dynamics without providing estimates of inland flood development.
Engineering criterion	Pathway	The article must analyse the performance and/or effectiveness of coastal protection infrastructure without providing maps of the extent of the coastal flood.
NBS criterion	Pathway	The article must not analyse the performance and/or effectiveness of NBS or ecosystems in reducing coastal flood risk without providing maps of the extent of the coastal flood.
Ecosystem criterion	Consequence	The article must not focus exclusively on the consequences of coastal flooding in terms of resulting modifications in ecosystem health and distribution.
Methodological criterion	Intervention	The article abstract must mention at least one of the method-related keywords utilised in the database query.
Post-event criterion	Context	The article must not focus exclusively on post-event flood mapping.
Spatial criteria	Outcome	At least one map proposed in the article must conform to the spatial criteria detailed in Section 2.2.
Groundwater criterion	-	The article must not focus exclusively on groundwater-driven flooding or on groundwater contribution to coastal flooding.
Residual criterion	-	The article should have been discarded in the previous selection phases.

During the data identification phase, research articles were retrieved based on a keyword search string and additional search parameters from two databases (Scopus and Web of Science) as detailed in Table 2 [17–19]. Early access papers, proceeding papers, book chapters and data papers were excluded from the search. This selective approach to publication types ensures that the review captures fully developed, peer-reviewed research that has undergone rigorous quality control processes, as journal publications typically follow more consistent reporting formats and validation requirements than other publication types.

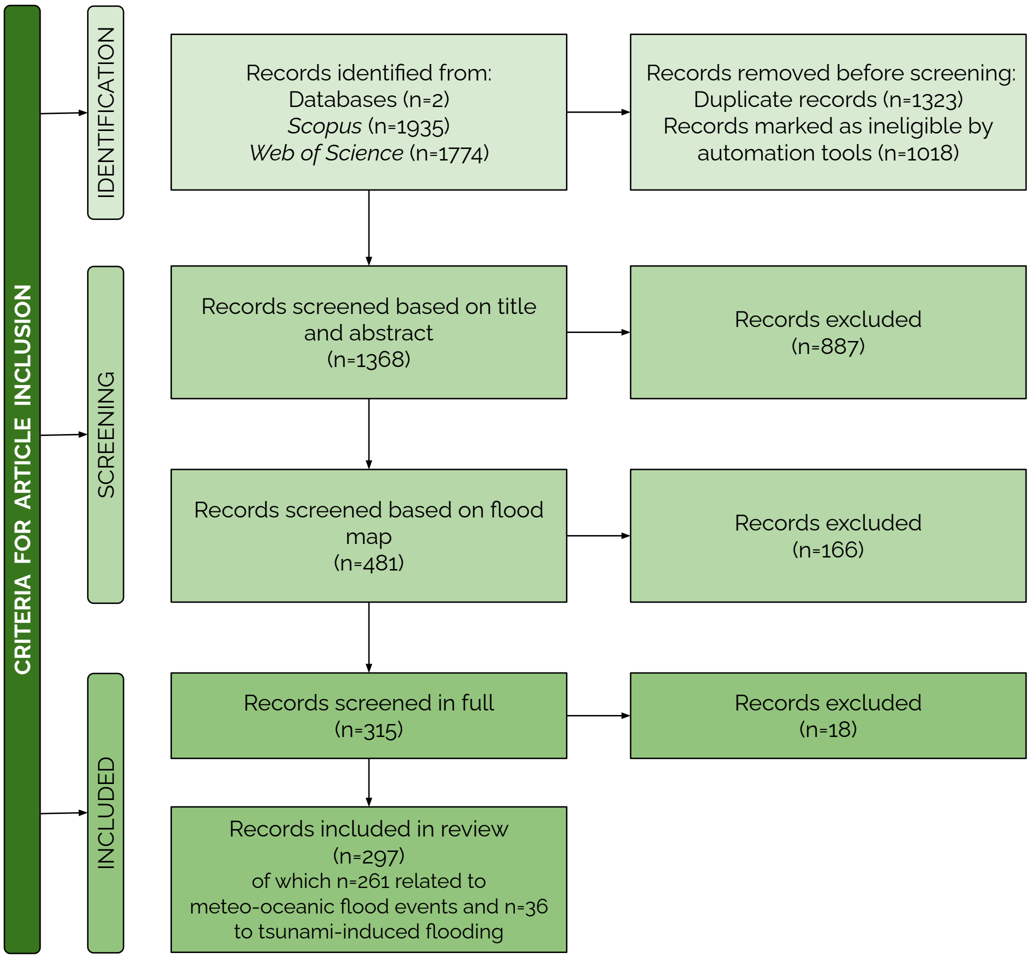

Figure 1. Flow diagram of article identification and screening procedures drafted according to PRISMA2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [20].

Citation data, bibliographical information, full abstract text and keywords were retrieved for identified articles. The two datasets were then filtered individually to remove within-dataset duplicates and articles for which relevant information was missing (i.e., missing DOI). The two datasets were then merged (n = 3709) and duplicates (n = 1323) were removed from the merged dataset. A series of automatic checks on the title and abstract were put in place based on regular expression selection. Specifically, the article abstract had to contain at least one of the keywords pertaining to the eligible research methodologies identified in the keyword search string, to further corroborate the automatic filtering carried out by the database search engine. Furthermore, the abstract was not to contain a series of words that strictly identify unrelated research fields. The final dataset eligible for screening consisted of 1368 articles.

The data screening phase was articulated into a first stage in which articles were manually selected based on the compliance of their abstract and title to the article selection criteria. A quick full-text examination was carried out whenever the title and abstract alone did not provide enough information to determine the fulfilment of one or more criteria. The second stage of the screening process was centred around the flood maps included in the articles. After visual examination, only articles providing a map conforming to the identified criteria for spatial flood representation (see Section 2.2) were selected. A total of 315 articles remained at the end of the screening process. A summary of the motivations for article elimination based on map characteristics is provided in Table 3.

Table 2. Parameters used for retrieval of studies from Scopus and Web of Science databases. Search was carried out on 21 February 2024.

	Scopus	Web of Science
Fields Searched	title, abstract, keywords	title, abstract, author keywords
Search String (full)	TITLE-ABS-KEY (coast* AND (flood* OR overflow* OR overtop* OR “inundation”) AND (“hazard” OR “susceptibility” OR “risk” OR “exposure” OR “vulnerability”) AND (map* OR model*) AND (“numerical” OR “physically-based” OR “hydrologic” OR “hydraulic” OR “hydrodynamic” OR “simplified” OR “GIS” OR “static” OR “empirical” OR “data-driven” OR “multi-criteria” OR mcd* OR “machine learning” OR “deep learning” OR “artificial intelligence” OR “statistical” OR indicator* OR “index”)) AND PUBYEAR > 2009 AND PUBYEAR < 2024 AND (LIMIT-TO (SUBJAREA, “ENVI”) OR LIMIT-TO (SUBJAREA, “EART”) OR LIMIT-TO (SUBJAREA, “ENGI”)) AND (LIMIT-TO (SRCTYPE, “j”)) AND (LIMIT-TO (LANGUAGE, “English”)) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “re”))	coast* AND (flood* OR overflow* OR overtop* OR “inundation”) AND (“hazard” OR “susceptibility” OR “risk” OR “exposure” OR “vulnerability”) AND (map* OR model*) AND (“numerical” OR “physically-based” OR “hydrologic” OR “hydraulic” OR “hydrodynamic” OR “simplified” OR “GIS” OR “static” OR “empirical” OR “data-driven” OR “multi-criteria” OR mcd* OR “machine learning” OR “deep learning” OR “artificial intelligence” OR “statistical” OR indicator* OR “index”)
Publication Years (inclusive)	2010–2023	2010–2023
Disciplinary Areas	Environmental science; Earth and planetary sciences; engineering	Environmental sciences ecology; water resources; geology; engineering; oceanography; physical geography
Document Types	Article; review	Article; review
Document Language	English	English

Table 3. Articles excluded during second stage of data screening process. Criteria for spatial representation of flood adopted in this review are detailed in Section 2.2.

Criterion	Explanation	Num. Articles
Map not provided	The article does not provide a map of the coastal flood over land.	54
Unsuitable map	The article provides a map which does not conform to eligibility criteria regarding the continuity in space and link to the physical hazard or susceptibility.	55
Residual filter criterion	The article should have been eliminated in the previous phases.	47
Article unavailable	The full text of the article could not be located or retrieved.	10

After data screening, remaining articles were examined in full. A total of 18 articles were eliminated during this phase, leading to a final set of 297 articles being included in the review. Of these, 261 were related to rapid-onset coastal flooding caused by meteo-oceanic extreme events, and 36 were related to inundation caused by tsunamis. A series of data charting items (Table 4) were filled out for each article pertaining to the first category, whereas the tsunami-related literature was assessed in less detail (see Section 5.6). The reader is referred to this article’s Supplementary Materials for a complete list of the reviewed articles.

Table 4. Data charting of items for articles included in review.

Data Charting Item	Retrieved Information
Methodology	Summary of the sequence of the main methodological steps performed in the analysis, mirroring the various DSPRC elements.
Models	List of model or methodology names (e.g., names of the specific hydrodynamic model used, or synthetic mention of methods, such as bathtub, MCDA, ML).
Climate Drivers/Scenarios	Specification of the use of observational data, establishment of scenarios, return times (RTs) and similar.
Compound Event	List of which drivers are being considered.
Ocean Dynamics	Name of model(s) utilised; kept empty if not modelled directly in the articles, e.g., if using pre-made datasets.
Pathway	Specification of model or methodology utilised to characterise the land–water boundary.
Type of Flood Map	E.g., flood hazard, flood vulnerability, flood risk, flood susceptibility.
Map Characteristics	Summary of the main distinguishing features of the map including scale, use of colours, use of satellite imagery, presence of multiple maps corresponding to multiple scenarios.
Vulnerability	Specification of any sub-component of vulnerability mapped in the article, if applicable.
Damage	Specification of the presence of estimates of flood damage either in monetary terms of by other means, if applicable.
Adaptation	Report of the adaptation measures proposed in the article, if applicable.
Special Focus	Specific economic sector(s) to which the flood assessment is referred to, if applicable (e.g., transport network, communication infrastructure, energy sector).
Discussion	Summary of the possible applications of the assessment presented in the article and the importance for different phases of the flood risk management process, if applicable.
Location	Location of the study area considered in the article.

2.1. The DSPRC Framework and Criteria

The Driver–Source–Pathway–Receptor–Consequence (DSPRC) [21] conceptual framework was utilised to systematise the retrieved literature and to establish some of the article selection criteria utilised throughout the literature selection process. Within the DSPRC framework, flood systems are represented as a linear succession of their individual components. Adopting this perspective allowed us in turn to systematise and streamline as much as possible both the characterisation of each component and their causal linkages, starting from the analysis of climate patterns and variation leading to the generation of extreme sea levels and moving towards the study of the consequences of coastal flooding on the socio-economic context of coastal communities [22–24]. The distinction between the different framework components is not clear-cut, and often articles can adopt quite a comprehensive approach in which multiple elements are addressed. This in turn required the studies retrieved and analysed to be attributed to multiple categories, depending on which of the framework components they focused on.

The DSPRC components are detailed below, along with the types of articles commonly focusing on them.

Driver (D): The main drivers behind the generation of sudden sea level variations in coastal areas can be either climate-related meteo-oceanic events or submarine earthquakes leading to tsunamis. Even if there might be some overlap between the two in terms of methodologies utilised to study them and research outcomes produced, the literature on tsunami-induced inundation represents a marginal interest of this literature review. A choice was made to exclude long-term SLR because of the different ranges of methodologies and policy concerns related to it when compared to rapid-onset flooding [25].

Source (S): The analysis of the source of rapid-onset coastal flooding relates to the modelling of oceanic and near-shore processes leading to the generation of extreme sea levels. Related research generally aims to estimate water level in coastal waters, often just until the water–land boundary. Articles considering fluvial-only of pluvial-only flooding in coastal areas were excluded from this review, whereas articles on compound coastal flooding were considered eligible.
Pathway (P): For rapid-onset coastal flooding, the analysis of the pathway entails addressing the passage of water from near-shore waters, through the water–land boundary, towards the inland receptor. Relevant literature examples include articles on hydrodynamic modelling and studies on the effectiveness of coastal protection infrastructure for reduction in the extent of incoming wave energy or inundation.
Receptor (R): The characterisation of the receptor requires the spatial identification of which inland portions of the coastal system might be affected by coastal flooding. Coverage of the receptor and its representation in space were considered fundamental requirements for the inclusion of articles in the review, thus excluding articles focusing exclusively on either one or a combination of the D, S, P or C components. Further criteria of the representation of the receptor were defined in terms of research outcome as detailed in Section 2.2.
Consequences (C): The estimation of the consequences of rapid-onset coastal flooding can be addressed through a multitude of disciplinary lenses, with respect to both socio-economic and natural systems. Some examples in the literature include structural appraisals of the effects of flooding on the building stock, analyses of flood-related casualties, economic damage estimation and policy-oriented research on the formulation of climate adaptation or mitigation measures.

2.2. PICOC-Related Criteria

In accordance with well-established guidelines for the development of systematic reviews, the scope of this analysis was defined in terms of which population (P), intervention (I), comparison (C), outcome (O) and context (C) (i.e., PICOC-related criteria) were to be addressed by analysed articles [16,26–28].

Population: The population comprises studies focusing on the modelling and mapping of rapid-onset flooding in coastal areas. No limitation was imposed regarding specific areas of interest; therefore, the work has a worldwide geographical scope.
Intervention: A broad range of methodologies were considered [28], including simplified and empirical models, physically based models, indicator-based models and data-driven and statistical models. Methodology-related search keywords (Table 2) were devised to be comprehensive yet generic enough to elicit a broad range of methods.
Comparison: Due to the broad scope adopted in terms of intervention, no comparison was considered.
Outcome (i.e., criteria for the spatial representation of the receptor): The articles had to portray spatial information on the receptor as a continuum in space and with some adherence to real-world physical characteristics or flood processes—for instance, the potential flood extent or the characteristics of the territory influencing susceptibility to floods. Flood maps referred to arbitrary or administrative units of space were excluded from the analysis [29].
Because of the recognised lack of clarity in the terminology related to flood risk, vulnerability and their individual components [30], as well as to keep a broad perspective on the different mapping needs required for coastal flood risk management, all the main flood-related types of maps (i.e., flood hazard, flood risk, flood vulnerability, flood susceptibility and their individual components) were considered as long as they conformed

to the spatial criteria mentioned above. The spatial scale of analysis was limited to exclude flood mapping at the large scale.

Context: The reviewed studies should be aimed at providing information in support of coastal risk prevention and preparedness, with the aim of delineating coastal risk zones and informing coastal adaptation policies. Thus, articles focusing exclusively on post-event coastal flood delineation were excluded.

3. The Coastal Flood System

As mentioned before, the coastal flood system can be synthesised in a systematic way in terms of the DSPRC framework. The same framework can also be utilised to organise studies in the literature on rapid-onset coastal flooding according to the components of the flood systems that represent their main focal points.

Therefore, the reviewed studies can ideally be described according to a two-dimensional matrix, in which one dimension is based on the methodology utilised and the other regards the DSPRC components addressed. In this section, the content of reviewed studies is organised based on the different components of the considered coastal flood system, as well as combinations thereof.

3.1. Compound Coastal Flooding

Compound flooding events are particularly relevant for coastal systems because of their location at the intersection between land and sea.

For this reason, particular attention was devoted to compound coastal floods in the reviewed literature. Out of the 261 articles considering flooding caused by meteo-oceanic extreme events, 78 referred to compound coastal flooding. Compound flooding was addressed from several points of view. In some instances, the drivers and sources of flooding were the focus of the analysis. The statistical characterisation of individual flood drivers and their interrelations was the main objective of most of the articles excluded based on the *climate criterion* detailed in Table 1. Nevertheless, several of the articles included in the final reviewed set addressed to an extent the statistical characterisation of compound coastal flooding events [31–33], with some instances presenting particularly thorough analyses [34]. The high uncertainty caused by climate change-induced combined changes in individual climate drivers and in their interactions was among the most relevant issues raised by the analysed literature on compound coastal flooding, because of the disruption of the fundamental assumption of stationarity [35]. Another relevant methodological issue was that of the superposition of different flooding processes vs. the need for monolithic simulations of compound flooding events, which are required to achieve more precise results [36].

A number of studies dealt with the identification of the main flood driver within a specific area or time horizon [37]. Santiago-Collazo et al. [38] showed that the main flood mechanism within compound flood hazards (hydrologic or coastal) can change through time depending on the flood scenario considered, highlighting how the dominant flood hazard in present-day hydrologically dominated watersheds might change in future long-term predictions.

A second class of articles focused on the hydrodynamic modelling of compound coastal flooding. Often, the marine component of compound events was addressed as a boundary condition in an overland flow model, utilising observed tidal levels, estimates of overtopping volumes or the output of ocean models [31,32,39–44]. Bates et al. [45] proposed one such example, in which the combined modelling of pluvial, fluvial and coastal flooding was carried out with the LISFLOOD-FP model for present and future climates along the conterminous United States, considering the water level at the coast measured from tide gauge stations as a downstream boundary condition.

Several studies focused specifically on the characterisation of compound coastal flooding from a spatial point of view, proposing methodologies for the delineation of zones for which one flood driver may be dominant. There is general agreement that the conformation of the coast and its watersheds can play a fundamental role in the location and extent of the three hydrologic, coastal and transition zones. However, different approaches have been adopted in the literature for this purpose, and no consensus exists about the definition of the transition zone [32]. Bilskie and Hagen [46] were among the first to present a methodology for the subdivision of coastal zones based on the source of the maximum simulated water level obtained in a coupled Simulating WAves Nearshore (SWAN [47]) + ADvanced CIRCulation model (ADCIRC [48]) simulation fed with different boundary conditions. Their approach was then adopted by other reviewed articles [38,49]. In subsequent research, the transition zone was further subdivided based on the dominance of flood depth from one source over the other, such as in Wijetunge and Neluwala [50] for compound storm surge and riverine sources and in Shi et al. [51] for compound rainfall and storm surge. In the latter, the authors also proposed an overview of the literature dealing with similar mapping of coastal zones based on the dominance of different drivers. Eilander et al. [52] proposed a globally applicable modelling framework where the Super-Fast INundation of CoastS (SFINCS [53]) model was used to obtain maps showing the difference in flood depth between compound and univariate flood events for the same area. Similar approaches were also proposed in [37,54] and in [55] for an akin subdivision for a river delta system.

Yet another class of articles aimed at proposing synthetic metrics for the spatial characterisation of compound flooding in coastal areas. One such instance is the Tide–Rainfall Flood Quotient (TRFQ) metric proposed by Mohanty et al. [56], with envisioned utilisation especially by low- and medium-income countries. The TRFQ is computed based on the ratio of area flooded during design storm tide-driven flood events over that flooded for rainfall-driven flood events, and can be used as *'an incisive measure to explicate the marginal/individual contribution'* [56] of different flood drivers within coastal catchments. Shen et al. [57] introduced the Transition Zone Index (TZI), defined as the ratio of the number of simulations in which transition zones share the same location divided by the total number of simulations. Higher TZI values identify areas where flooding is likely to be the product of the interactions of storm tide and rainfall, eventually supporting the choice of suitable flood mitigation approaches.

Mitu et al. [39] proposed the use of topographic indices for the identification of areas for which a single flood driver might be most relevant.

3.2. Pathway Characterisation

The characterisation of the pathway entails the study of the coast and its structures—both natural and man-made—and the analysis of the movement of water from the sea inland. Among reviewed articles, some highlighted the generalised paucity of research on integrated atmosphere–ocean–coast–overtopping modelling [58]. Others addressed more specifically the shortcomings and complexity in the study of the movement of water from the sea, through coastal structures, towards emergent land during coastal flooding events, stressing the need to integrate tide-surge, wave and flood modelling in unified frameworks in order to accurately predict the flooding due to wave overtopping [58,59]. Some of the analysed articles presented overviews of the methodologies utilised to model the passage of water through the pathway during overtopping events and in general for coastal inundation [60,61]. In the simplest approaches utilised for this purpose, overtopping discharges are accounted for as source points in high-resolution models and then computed with empirical formulas (with the EurOtop methodology as a notable instance thereof [62]). In more complex methodologies, process-based solvers are applied in one horizontal dimension along a cross-shore transect. Le Roy et al. [60] highlighted that such empirical and 1D models are typically characterised by limits in the spatial and temporal accuracy, which might be particularly relevant in complex coastal urban areas. Finally, in the most complex methodologies—utilised in only a minority of the reviewed literature—the two horizontal dimensions are explicitly represented in the model in order to better account for the hydro- and geomorphological variability in complex coastal environments. Especially in studies applied to sea-driven inundation only, the pathway was most commonly approximated as a simple threshold between the total water level registered at the coast and the land (see Section 4.1).

Another branch of the reviewed literature approached the pathway in terms of an in-depth study of the structure of the coast itself, and of its influence on hydrodynamics in near-shore waters or within complex coastal systems such as estuaries and channels. In some instances, the main objective of the analysis was the establishment of different scenarios of coastal morphology and the study of the related variations of water dynamics, occasionally also considering combined changes in climate conditions. One such example was presented by Mansur et al. [63], in which the capacity of inland penetration of storm surge was analysed for a scenario of depth increase in a navigational channel located in an estuarine region; the authors concluded that such a modification could lead to substantial increases in inland peak water levels, peak volumetric flow rates and flooded area. Orton et al. [64] studied the influence of landscape changes (urbanisation, changes in habitats) on storm tide increase, showing the most determinant factors to be anthropogenic changes to estuary depth and inlet depth and width for their study area in New York City. Other studies [65,66] accounted for storm-related modifications to coastal morphology using the morphodynamic model XBeach [67], within numerical simulations of surge and wave conditions.

The precise representation of coastal defence structures in coastal flooding simulations for a specific location and point in time was the focus of the analysis of a number of reviewed articles [25,68]. Sometimes, advanced remote sensing techniques were utilised to precisely image such infrastructure [69]. Ke et al. [70] highlighted that few studies in the literature have explicitly considered the effects of the failure of coastal flood defences. The effects on coastal inundation of fixed protective coastal structures that were originally developed for purposes other than flood defence—such as the reclaiming of coastal wetlands—were evaluated by Christie et al. [71].

Another class of articles focused on the characterisation of coastal ecosystems and the quantification of their role as Nature-Based Solutions (NBSs) in the dampening of adverse effects of coastal inundation. Examples of NBSs that intervene in the pathway of coastal flooding are the seagrass meadows and artificial dunes considered in Unguendoli et al. [72]. Banan-Dallalian et al. [73] modelled coastal inundation caused by a tropical cyclone (TC) event with and without a hypothetical mangrove forest along the affected coastline, determining a relevant local Manning coefficient and the mangrove forest width. Results of their study showed that mangrove forests can contribute to reductions in both maximum flood depth and maximum flow velocity. Cassalho et al. [74] found that coastal wetlands can contribute to the attenuation of significant wave height as water propagates inland during storm events, even if maximum water depth is not significantly reduced. The role of foredune ridges (and erosion processes thereof) in the modification of coastal flooding processes were also analysed in the reviewed literature in an article by Danchenkov et al. [75].

3.3. Receptor

In this work, the main representation of the flood receptor has been considered the flood map, to which Section 5 is dedicated. Depending on the main objective of the study, the receptor might also be investigated more in depth, for instance, by explicitly accounting for the effects of variations in the inland coastal territory on coastal flooding. Though this type of analysis was seldom found in the analysed literature, Canters et al. [76] proposed a notable example of it. They used a cellular automata (CA) method to model variations in the land use/land cover of the study area to assess resulting variations in coastal flood risk deriving from two set scenarios of flood hazard, whereby the dynamically changing component within the flood system was the receptor.

3.4. Consequences

A significant portion of the reviewed articles analysed flood consequences, with a variety of different focuses and methodologies. For some of these, the estimation of flood-related damage was the primary objective of their analysis [77,78]. The most common approach adopted in these studies was the transformation of flood hazard information into information on flood consequences through depth–damage functions, at different levels of detail. To achieve this, some articles referenced well-established depth–damage curves such as those devised by the US Federal Emergency Management Agency (FEMA) [79]. Others formulated bespoke damage functions provided by local authorities [80], or adapted pre-existing data and functions to their study area [81].

In some instances, proper economic and damage models were utilised, such as the Delft-Fast Impact Assessment Tool (Delft-FIAT) [82], the FEMA HAZUZ platform [83] or the economic module of the Coastal Louisiana Risk Assessment (CLARA) model [84].

In some cases, spatially coarse information on land cover was utilised to characterise the type of land affected, either because of the lack of more detailed information or due to the characteristics of the receptor itself (e.g., primarily agricultural land [85]). Other studies highlighted that structural building properties are key fragility determining factors, also affecting overall flood vulnerability and related damages [86]. The need to carry out analyses at a higher level of resolution was raised, including detailed information on building age, height, configuration and construction material other than the usual depth–damage relationship [78,87].

Flood damage and economic consequences were in some cases accounted for within indicator-based methodologies. Spaulding et al. [87] formulated the Coastal Environmental Risk Index (CERI)—a methodology used to estimate expected infrastructure damage—which was also utilised in subsequent analysed publications [88]. Yan et al. [89] included sub-indicators of fiscal revenue in their assessment. Lopes et al. [90] assessed flood-related consequences within a DSPRC framework based on asset value, susceptibility and exposure, considering a wide variety of assets (*'inhabitants, land use, roads, buildings, classified areas and sensible habitats'*). Armaroli et al. [91] proposed an integrated hazard and impact modelling approach—the Integrated Disruption Assessment (INDRA)—linking numerical modelling for coastal flood hazard identification with Multiple-Criteria Decision Analysis (MCDA) to quantify direct and indirect impacts of coastal flooding based on eight standardised indicators.

A limited amount of studies addressed themes related to flood consequences in terms of environmental equity and justice, with the aim of identifying if flood impacts disproportionately affect minority, low-income or otherwise vulnerable communities. Analysed studies attained mixed results, with some examples showing that some ethnicities tend to be predominantly affected by different flood drivers (e.g., inland vs. coastal) [92] and other studies highlighting the higher relevance of socio-economic status indicators (age, gender, education) in determining disproportionate environmental inequities for flood risk when compared to ethnicity or race [93].

3.5. Addressing Multiple DSPRC Components

A limited portion of the reviewed articles proposed comprehensive studies addressing multiple DSPRC framework components, sometimes explicitly mirroring the framework structure in the study design [88]. Halsnæs et al. [94] linked climate scenarios, flood models, Geographic Information System (GIS)-based flood impact mapping and damage cost estimation, and further completed the analysis by discussing the policy implications of their research in terms of cost-effective adaptation planning for two Danish coastal urban areas. Eilander et al. [54] proposed a study of compound coastal flood risk, including univariate extreme value analysis, hazard impact modelling, damage estimation and a discussion of different adaptation and mitigation strategies based on their efficacy to address extreme events of different Return Times (RTs). Wang et al. [81] proposed a study composed of a statistical analysis of typhoon-related storm surge, numerical ocean modelling, inundation modelling with GIS, assessment of direct economic losses with depth-damage functions and a social vulnerability analysis.

Comprehensive studies able to streamline the complexity of flood processes and support risk management can represent desirable approaches. However, it is noteworthy that some reviewed of the literature cautions against the high uncertainty, errors and propagation thereof that may be embedded in outputs of complex methodology chains, which might require care in the communication and implementation of assessment results [70].

4. Methodologies to Model Rapid-Onset Coastal Flooding

Five main types of methodologies were identified in the literature to model rapid-onset coastal flooding, namely, static inundation models, raster-based approaches, index-based methodologies, data-driven methodologies and numerical methodologies. A significant portion of analysed articles utilised multiple methodologies in varying combinations, which hindered a precise estimation of the relative significance of individual classes of methodologies. At the same time, it should be acknowledged that methodologies have been aggregated in broad classes for the purpose of clarity, but that the boundaries among different methods might not be as well defined.

4.1. Static Inundation Models

Static—or "bathtub" or planar projection—models are methodologies in which all locations below a threshold water level are considered flooded, several variations of which have been proposed in the literature [95] mostly for marine-driven inundation and to a lesser extent for fluvial flooding. Static models are used mainly to obtain first approximation estimates of the potential inundation extent of flooding events because of their lower computational and data requirements compared to those of hydrodynamic or data-driven methodologies [96]. Though, they are characterised by significant drawbacks as they have been shown—with very rare exceptions [97]—to generally be less precise than process-based models and to overestimate the flood extent [98–102], because they fail to account for the physical processes underlying the flooding event and neglect the hydrological connectivity of the terrain. As highlighted by Liu et al. [103], a further differentiation can be made for the bathtub approach based on whether it is used to approximate non-source or source floods. The former are exemplified by situations of well-distributed water over a given area, such as a rainstorm over a large area where all low-lying land might be flooded. The latter describes instead a flood pulse flushing though a broken barrier such as in storm surge flooding spreading from a localised embankment break, in which case accounting for circulating conditions is even more crucial than for non-source floods.

The bathtub approach was utilised frequently in the analysed literature: 62 out of the 261 reviewed articles utilised it to some extent. The method was adopted in flood hazard studies to approximate the pathway between sea and land by projecting onto land in a relatively straightforward manner the water level obtained either from observational records or with models that solved the ocean and shallow-water hydrodynamics until the shoreline demarcation. In some of these instances [97–99,104,105], the static model was utilised as a benchmark against which to compare the performance of more complex methodologies.

The bathtub method was also utilised in studies adopting more comprehensive outlooks on coastal flood vulnerability or risk—most often utilising indicator-based methodologies (see Section 4.3)—to identify the hazard zone in a straightforward manner and then integrate such information with other socio-economic data [106–108].

Other articles focused instead on proposing some methodological improvements to the simplest form of the bathtub approach in order to address some of its limitations. For instance, Carneiro-Barros et al. [109] proposed a Tilted Bathtub Approach (TBTA) in which the relation between maximum overwash extension and the corresponding wave run-up values is more precisely defined utilising historical records of flooding for a particular location and event for validation. Enriquez et al. [96] proposed the *MatFlood* algorithm, which improves upon the conventional bathtub approach by allowing for spatially varying the water level within the water body from which the flood originates, and through the inclusion of an inverse distance reduction factor to compensate the possible overestimation of both flood extent and depth. Similar considerations of varying source water level were addressed by Breilh et al. [110], who compared different types of static inundation models (homogeneous or space-varying sea level) against a semi-dynamic method (surge overflowing method).

Attempts at introducing a measure of probability and uncertainty of inundation in static inundation models were also proposed in the reviewed literature by Fereshtehpour and Karamouz [111] and Kovanen et al. [112]. Both studies utilised probabilistic Monte Carlo approaches to generate different realisations of the terrain data within bathtub models with enforced hydrological connectivity. In the first case, the authors aimed to assess the influence of Digital Elevation Model (DEM) resolution on the inundation results. In the second study, the research objective was to obtain a *stochastic bathtub model* by generating both varying (equally probable) instances of terrain and varying instances of water level to obtain a cell-wise probability of flooding in the study area.

4.2. Other Raster-Based Approaches

Raster-based methods can represent efficient approaches in contexts where large-scale flood estimations are required at high spatial resolutions [113]. LISFLOOD-FP [114] is a widely used example of a physically based flood inundation model integrated with DEM raster data, originally designed to reduce the representation of floodplain hydraulics '*to the minimum necessary to achieve acceptable predictions*'. Though not originally developed for the study of coastal inundation, LISFLOOD-FP was extensively adopted in the reviewed literature to study both marine-driven and compound flooding in coastal areas, depending on which combinations of upstream and downstream (coastal) boundary conditions were provided to the model (e.g., [91,105,109,115–117] for marine-driven inundation and [45,118–120] for compound coastal flooding). An investigation of the influence of DEM quality and resolution on LISFLOOD-FP performance was proposed by

Seenath [121]. In some instances [37,122,123], LISFLOOD-FP was implemented as the hydrodynamic component of the integrated hydraulic and landscape evolution model CAESAR-Lisflood [124].

Makris et al. [113] proposed *CoastFLOOD*, a high-resolution *'storage-cell, mass balance flood inundation'* model, in which the problem of coastal inundation is approached as a wet/dry cell storage problem and semi-analytic hydraulic equations for continuity and volumetric flow rates are solved within a finely discretised study domain. Another raster-based inundation model for coastal inundation that solves simplified versions of shallow-water equations for each cell was also implemented by Favaretto et al. [125]. Zheng and Sun [126] proposed a similar approach that utilises principles of cellular automata (CA) to update the grid cell state.

In addition to the aforementioned process-based models closely linked to the raster data structure, other types of low-complexity raster-based flood mapping methods are also included in this section. Hydrogeomorphic classifiers based on the height above the nearest drainage (HAND; i.e., factor H) have found wide application in the literature for the rapid identification of the floodplain, most notably for inland flooding. Jafarzadegan et al. [127] noted that some adjustments are required to adapt these methods for use in coastal low-lying regions. To that end, the authors proposed a classifier similar to HAND developed specifically for coastal wetlands, estuaries and deltas, based on the distance from the nearest drainage point (i.e., factor D) as well as factor H, since factor D had been previously shown to outperform factor H in particularly flat regions.

4.3. Index-Based Methodologies

Index-based methodologies are approaches aimed at providing synthetic measures of multifaceted concepts composed by several components, such as vulnerability and risk. These methodologies generally involve the selection of which data to use as proxies of such individual components (i.e., indicators) and their aggregation into the final measure of the complex concept (i.e., index) [128].

The spatial criteria for the inclusion of articles in this review required flood maps to be presented in a spatially continuous way and to not be referred to arbitrary units of space, such as purely administrative regions. It was assumed that imposing these limitations would elicit spatialised indices retaining to a certain extent a link to the physical processes involved in flooding, by accounting for the hazard or the physical susceptibility deriving from intrinsic land characteristics. Nevertheless, the second part of the screening process (see Figure 1 and Table 3) highlighted how often articles utilising index-based methods did not meet this requirement.

This class of methodologies was most often utilised in studies proposing comprehensive assessments of vulnerability and risk to coastal flooding. From a conceptual point of view, the analysis confirmed clear conceptual confusion and lack of standardisation in the definition of these concepts and their components, with a variety of different data, aggregation techniques and miscellaneous terminology utilised in the reviewed articles. From a terminological point of view, it can be highlighted that even if some difference exists between the two, the terms index and indicator were used quite interchangeably.

The Coastal Vulnerability Index (CVI) [129,130] represents the most prevalent method in this class of reviewed literature. It is obtained as a combination of a physical vulnerability index and of a socio-economic vulnerability index, defined differently depending on the local information needs, geographic peculiarities and data availability. Mirroring this general structure, several studies utilised overlays of diverse information on natural and societal characteristics for the definition of aggregate measures of vulnerability and risk. The natural characteristics considered pertained most often to the identification of the flood hazard zone by various means such as post-event flood imagery [131], the bathtub model [56,106–108,132–134], hydrodynamic simulations [135–137] or flood hazard maps provided in previous studies or distributed as widely available data for the same area [89,138–140]. In other cases, studies considered the physical geography of the study area with data ascribable to land-related flood susceptibility factors [141–145].

The DSPRC framework was utilised in some studies to orient the choice of indicators and general methodologies utilised [89,107].

From a methodological point of view, GIS-based MCDA was commonly utilised to choose data for inclusion in the aggregate index as well as to rank the relative indicator importance, mirroring the findings of Avila-Aceves et al. [2].

4.4. Data-Driven Methodologies

Data-driven methodologies are characterised by the absence of *a priori* assumptions about the underlying functioning of a system, and are aimed at estimating functions for its approximation based on observations. This umbrella term was utilised in this review to refer to a broad lexicon utilised by individual studies, including terms such as artificial intelligence, machine learning (ML) and statistical learning.

Data-driven methodologies were used in the reviewed literature for three main purposes.

A first category of studies utilised ML to build surrogates for high-fidelity physics-based models for ocean dynamics and the inland propagation of floods [146,147]. An overview of the literature utilising ML and climate data to model ocean circulation was proposed by Pachev et al. [148] within an article utilising ML methods as a stand-in for the well-established ADCIRC. As noted by López-Lopera et al. [149], usually surrogate ML models adopt scalar representations of hydrological forcing conditions (inputs) and flood events (outputs), neglecting that inputs are time series and outputs are floods that propagate inland. To improve upon these shortcomings, they used a multioutput Gaussian process-based model that correlates functional inputs and spatial locations, which can be used with time-varying inputs and to provide information on spatially varying inland coastal flooding. ML surrogate models were also used in the analysed literature for compound coastal flooding. For instance, Bass and Bedient [150] proposed a metamodelling study of compound storm surge and rainfall-runoff, emulating ADCIRC, SWAN, the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) and the Hydrologic Engineering Center-River Analysis System (HEC-RAS) models with the aim to predict peak inundation levels (in 2D) using hurricane landfall characteristics as inputs.

Data-driven surrogates are especially favourable in contexts that require shorter model runtimes, such as in early-warning systems (EWSs). Within this context, Chondros et al. [151] proposed an integrated methodological approach consisting of a hindcast and a forecast framework only requiring wave characteristics and sea-water-level elevation to predict maximum flood depths in areas of interest. Idier et al. [152] utilised classifier-based metamodels to estimate indicators originally computed based on the outputs of a phase-resolving numerical model (Simulating WAves till SHore (SWASH)), within a user-oriented EWS framework aimed at bridging the gap between state-of-the-art modelling and decision maker information needs.

A second class of articles utilised data-driven methodologies to assess flood susceptibility, with the aim to identify all inland areas which might be negatively affected by flood hazards because of their intrinsic characteristics. Most often the analysis was characterised as a pixel-wise supervised learning task based on the estimation of the relationship between the location of flood events (either observed or modelled) and relevant features of the territory (e.g., terrain, topography, geomorphology). The latter were usually represented as a stack of two-dimensional data covering the study area. Since most of these predictors can play a role in flooding of many different origins, the characterisation of the article as pertaining to coastal flooding for the purpose of its inclusion in the review was based mostly on the study area and the description of past flood events proposed by the authors [153–155].

The inclusion of climate-related predictors is not uncommon in studies addressing pluvial and fluvial flood susceptibility, insofar as some precipitation datasets can be easily represented in a two-dimensional way and stacked alongside other terrain-related predictors.This is not true for most climate datasets relevant for marine-driven inundation. Hasan et al. [156] included the distance from cyclone tracks among the flood susceptibility predictors; yet, the spatial interpolation for some of the other climate data utilised (e.g., mean sea level) was not explained in detail in the article.

Muñoz et al. [157] proposed a study adjacent to this category, in which a convolutional neural network (CNN) trained on satellite data and modelled flood ground truth was used along with other data fusion techniques to produce multiclass land cover classification, including classes of permanent water and floodwater.

The third class of articles utilised data-driven methodologies aimed at estimating the consequences of coastal flooding, for instance, to obtain refined exposure datasets (affected population, casualties, GDP) [158], to predict property damage [77] and total losses [80], and to predict the spatialised annual probability of flooding using data from insurance claims datasets [159].

4.5. Numerical Methodologies

Numerical methodologies are computational implementations of mathematical approximations of physical laws. They can be used in flood-related research to describe the dynamic behaviour of water with varying assumptions and simplifications depending on the scale and focus of the analysis [160].

Articles utilising numerical models represented the most prevalent class in the analysed literature. Physically based numerical models were very numerous and covered a wide array of represented process, since they can be utilised to model variable combinations of the driver, source, pathway and receptor components of the coastal flood framework. Several articles proposed diagrams representing the modelling chain of sea-driven inundation [161], showing the links and coupling between the modelling of meteorological conditions, ocean modelling—at the global, regional and local scale—and flood models for the representation of coastal inundation and the inland flood propagation.

A detailed description of all the main characteristics, data inputs and outputs, usage and limitations of the numerous numerical models used to simulate the several components of the coastal flood system is outside the scope of this work. However, a few of the reviewed articles proposed thorough portrayals of some of the models utilised to simulate coastal flooding over land. The reader is referred to Androulidakis et al. [162] for an overview of existing 2-D flood models developed for coastal inundation at various levels of complexity and to Joyce et al. [163] for a selection of 1D, 2D and 3D hydrological models. Nahon et al. [61] addressed methodologies for modelling wave overtopping discharges. Makris et al. [113] and Son et al. [40] proposed detailed lists of—respectively, and with some overlaps—flood models for coastal urban systems (including mention of required precipitation, upstream, downstream and coastal boundary conditions) and of 2D inundation model suites developed for river flooding but adapted to the study of coastal flooding.

The range of numerical models utilised in the reviewed articles extended further than those mentioned in the studies referred to above, because no limitation was established pertaining to which DSPRC components needed to be addressed by the model. Even though some ocean circulation models can also be used to model coastal inundation (e.g., ADCIRC, or the Finite-Volume Coastal Ocean Model (FVCOM) [164]), a non-negligible portion of the reviewed literature utilised numerical physically based models for the description of ocean and coastal waters (e.g., storm surge models unable to account for inundation over land such as the High-Resolution Storm Surge (HiReSS [165]) model [113] or wave models [71,120,166]), and then addressed coastal inundation with simplified methodologies (see Section 4.1) or as input to overland flow models. In articles dealing with compound coastal flooding and considering pluvial and fluvial processes, the range of methods widened further, including models for the simulation of rainfall-runoff processes to provide precipitation and upstream river boundary conditions (e.g., HEC-HMS) [43,167].

A non-negligible portion of analysed articles (approximately 9% of the articles on flooding caused by meteo-oceanic extreme events) utilised ADCIRC to simulate coastal inundation over land and to model surge and waves when coupled with the shallow-water circulation model and spectral wave model SWAN [40,168].

Matters related to model coupling within modelling chains were frequently considered in reviewed articles utilising numerical methodologies. A relevant instance thereof with regards to compound flooding was found in Bush et al. [169], in which different coupling modes for the ADCIRC and HEC-RAS models were investigated.

Another matter of importance emphasised in the reviewed literature was the definition of the spatial representation of the input coastal boundary conditions for models used to simulate coastal flooding overland: Johnson [84] highlighted how the definition of a spatially homogeneous *surge surface* from the origin water body towards land is a widely utilised and convenient abstraction that might lead in some instances to misrepresentations of the spatial development of floods.

4.6. Other Methodologies

Moradi et al. [170] used an integrated GIS and System Dynamics (SDs) model to estimate direct and indirect damage of coastal storms. Some articles utilised Bayesian Networks (BNs) for different purposes, especially to surrogate process-based models, and relate offshore hydraulic conditions to inland flood conditions and indicators of impact [171,172], or in general to represent the relationships among different elements of the coastal floodplain system [173].

Coquet et al. [174] and Elineau et al. [175] used sketch maps collected from survey respondents in coastal areas with the objective of estimating potential bias in the perception of flood risk. Sketch maps produced by respondents regarding the identification of areas potentially or previously affected by flooding were compared to the outputs of hydrodynamic modelling, showing a generalised misperception of flood risk.

5. Types of Flood Maps

The presence of a flood-related map compliant with the spatial criteria identified in Section 2.2 was a fundamental requirement for the inclusion of articles in this review. Maps of different types were featured in the analysed literature, including flood hazard, flood susceptibility, flood vulnerability, flood risk and maps of individual components of the above. The definitions of flood hazard and susceptibility maps proposed by Bentivoglio et al. [6] were adopted in this work. Because of the aforementioned lack of a standardised lexicon and methodologies for the assessment of risk and vulnerability, the classification of reviewed maps within these two categories was sometimes uncertain. As a general rule, risk maps were assumed to include information on the hazard, whereas this was not required for vulnerability maps.

The cartographic representation of the coast was among the themes analysed in the review by Bukvic et al. [176], who highlighted that no consensus exists for the delimitation of the coastal area of reference, and addressed some of the cartographic best practices that should be taken into account to communicate assessment results—in their case, specifically for coastal vulnerability mapping. Chen et al. [177] addressed cartographic best practices for hurricane evacuation maps, some of which are applicable in general to all the articles reviewed. In general, these works indicated that map products should be tailored to their context of application, sometimes also involving local stakeholders and beneficiaries of the analyses in the definition of the map characteristics depending on specific communication needs. At the same time, cartographic clarity in terms of fundamental elements such as communication of scale, use of colours and inclusion of data labels should be guaranteed.

The reviewed studies devoted varying levels of attention to the mapping product they presented depending on its role within the analysis presented. For a notable number of the reviewed articles—especially those presenting hydrodynamic simulations in the field of oceanography or engineering—the role of the flood (hazard) map within the study was mostly to support the results of the analysis, but no further utilisation was envisioned for it in terms of informing policy. This in turn is likely to be the cause of the non-compliance of these maps to cartographic guidelines mentioned above, which often complicates the interpretation of study results for outside users. Substantially different maps were proposed within articles that addressed to some extent the potential applications of the study results within the coastal flood risk management process. In these cases, proposed maps were more in line with the above guidelines, and sometimes highlighted features relevant for the definition of flood exposure and overall vulnerability.

The following sections depict the characteristics of the main map types proposed within reviewed articles.

5.1. Flood Hazard Maps

The majority of reviewed studies (241 out of the 261 articles addressing coastal floods of meteo-oceanic origin) proposed flood hazard maps, either alone or in conjunction with other types of maps. Most of the hazard maps proposed represented flood extent and depth, and to a much lesser extent, other relevant flood variables such as flood velocity [178] and time of submersion, or were maps of the time of maximum flood hazard for different portions of the coastal area considered [74]. In some instances, multiple flood hazard maps referring to different timestamps during a simulated coastal storm event were included in a time-lapse-like manner [167,179,180]. Even if some studies proposing hydrodynamic simulations mentioned that information on both flood depth and flood probability should be supplied for a complete definition of flood hazard [90], most of the studies proposing flood hazard maps did not consider probability. In some of the studies that did, the flooding probability was addressed by considering the *chance of flooding* map associated with inundation extent and maximum flood height [181], or the annual probability of areas being in the 1% flood zone [182]. A similar treatment of flooding probability embedded in hazard information was adopted by articles utilising 100-year FEMA floodplain maps. These—and similar national datasets of flood hazards—were commonly adopted as an indication of the hazard zone in studies which did not focus specifically on hazard modelling but needed an indication of it to address more comprehensive measures of risk, vulnerability or other components of the DSPRC framework [93,138]. Nevertheless, in most cases, information on the probability associated with a given flood event was conveyed through the article text but not associated to the map provided.

Most of the reviewed studies proposed flood hazard maps in which flood depth (in metres) was represented in a sequential colour scale, often associating darker blue tones to higher flood depths. Examples of diverging colour scales or colour scales based on other tones were rarer.

As addressed in more detail in Section 3.1, some articles provided maps portraying the spatial subdivision of coastal-dominated, hydrologically dominated and compound zones within the area considered [46], along with information on the flood depth.

Independent of the variable represented, flood hazard maps closely retrace the distribution of floodwater in space. These data are superimposed upon basemaps which generally vary between DEM-like greyscale backgrounds [54] and satellite imagery [91], also depending on the scale of the analysis. In rarer instances, synthetic solid-colour backgrounds [74] or stylised cartographic representations (e.g., OpenStreetMap) of coastal urban areas were utilised as basemaps.

A small proportion of articles highlighted relevant exposed assets within the map, such as important infrastructure and culturally or socially relevant locations [91,94]. It was noticed that when compared to the very symbolic representations utilised for other map types, flood hazard maps more often showed the whole study region considered and its surroundings, and provided a more specific portrayal of terrain and urban characteristics.

5.2. Flood Vulnerability Maps

According to the IPCC [183], vulnerability to a given natural hazard can be expressed as a combination of the system's exposure, sensitivity and adaptive capacity. Even though a multitude of different interpretations have been given to this concept, in general, vulnerability can further be subdivided between biophysical and socio-economic components. With regards to vulnerability to rapid-onset coastal flooding, the reviewed literature adopted a broad spectrum of interpretations, from articles focusing exclusively on biophysical vulnerability, to those considering a mix of the two components, to those considering exclusively socio-economic vulnerability [141,154]. Instances of the former approach [143] exclusively considered physical features of the area—such as land cover data [184,185] or geomorphological characteristics [142]—as a proxy for the local ability to cope with hazards. As a consequence, the spatial representation of vulnerability corresponded to the physical distribution of the geographical element which was being considered. In the latter approach, vulnerability was computed based on socio-economic indicators exclusively, and was mapped referring to spatial units that are exclusively administrative in nature. This way of representing (socio-economic) vulnerability has long been the most commonly utilised approach in the literature [186]. A middle-ground approach can consider both components of vulnerability, for which in-depth analyses can be found especially within studies focusing specifically on vulnerability and explicitly addressing the data selection and aggregation processes.

The spatial representation of vulnerability can in turn vary depending on the data aggregation strategy adopted by the individual study. In some instances [108], maps of overall vulnerability conveyed some information about the biophysical processes considered. For instance, some studies [89,186] accounted for expected flood damage computed on the base of the estimated flood depth of affected infrastructure, thus retaining spatialised flood information within the vulnerability map. A good example of this approach can be found in Rey et al. [186]. Utilising a different approach, Weis et al. [140] included information on the potential flood extent within the estimation of exposure. However, the final vulnerability map adopted the same spatial representation of sensitivity and adaptive capacity, which were based on purely administrative units.

Overall, the spatial representation of vulnerability as being referred to purely administrative units was predominant, based on the combination of *middle-ground* approaches of the latter kind with approaches considering socio-economic indicators exclusively. Regardless of the adopted approach, vulnerability was usually mapped over the study area as a dimensionless ranked index. Most analysed articles utilised five vulnerability classes and a diverging colour scale with green (or, less commonly, blue) associated with lower vulnerability and red associated with higher vulnerability. In some instances, the vulnerability map was not self-explanatory because numbered ranks were associated with colours in the map legend, without a consistent use of higher or lower numbers mirroring higher or lower vulnerability. This in turn required the reader to search for the rank explanation within the article text.

Often, flood vulnerability maps were proposed in a very stylised manner, covering the whole study region without providing information on relevant local features, terrain or on the surrounding areas outside of the study region.

5.3. Flood Risk Maps

In line with the previous relevant literature addressing the inconsistencies in the definition of the concept of risk and its operationalisation, this review highlights that no consensus emerges among analysed studies on the choice of which components to consider and how to aggregate them in a concise measure of risk. Risk was represented at times as a combination of hazard and vulnerability [136], at times as a combination of hazard, vulnerability and exposure [133], and by others considering hazard, exposure and vulnerability as well as considering a further subdivision of the latter in its physical and socio-economic components [81], to cite but a few. A thorough breakdown of the numerous different methodologies utilised for coastal flood risk assessment, as well as an analysis of the different ranking methodologies utilised for risk classification are out of the scope of this review. A focus on the differences in the spatial representation of risk that ensue from and mirror these methodological differences is adopted here. A relevant proportion of studies presenting flood risk maps did so within a broad risk analysis framework, which allowed us to compare the spatial representation of the different components of risk considered.

In general—however one defines it—flood risk is a composite indicator of natural processes (i.e., hazard) and socio-economic factors, for which different spatial representations are appropriate (see Sections 5.1 and 5.2). Depending on the individual study, risk maps can adopt the same cartographic conventions of vulnerability maps, since they are referred to the same administrative units even though they contain some form of underlying information concerning the hazard level within such boundaries [81,136]. Within a similar perspective, the spatial representation of risk can be even more abstract; for instance, in Martinelli et al. [187], risk was referred to as a series of lines parallel to the coast, for different sections of it. In fact, some of the flood risk maps proposed in the analysed articles did not conform to the spatial criteria for the selection of studies as defined in Section 2.2; these studies were included in the review exclusively on the grounds of the flood hazard maps presented in conjunction with flood risk maps. In other cases, flood risk maps veered more towards the type of spatial representation of flood hazard maps, highlighting risk within portions identified by the flood hazard [90,132,184,185,188]. Differently from flood hazard maps, flood risk maps usually represented ranked classes and not quantitative flood variables that can be represented with a continuous colour scale. For this reason, a diverging colour scale strategy similar to that described for vulnerability was commonly adopted.

5.4. Flood Susceptibility Maps

Seven of the reviewed articles proposed flood susceptibility maps. Generally, these studies were carried out with data-driven methodologies aimed at estimating the relationship between the location of past flood events and a series of predictors, commonly called flood influencing/inducing factors [153,155,156,189,190]. Eventually, all locations within the study area are classified as potentially being exposed to floods based on their intrinsic characteristics, and a continuous map of susceptibility is proposed for the study region considered. Often maps of individual predictors and maps of the flood inventory data used as ground truth were also included in the study, in addition to the final susceptibility map [22,153,155,156,189–191].

Flood susceptibility maps are obtained from and refer to purely physical features of the territory, without any additional data pertaining to socio-economic characteristics. In this sense, flood susceptibility maps more closely resemble flood hazard maps than flood vulnerability maps. Nevertheless, they share with the latter the qualitative nature of the data being represented and some of the cartographic choices mentioned before. In flood susceptibility maps, each portion of the study area is generally assigned to one of a series of qualitative classes corresponding to increasing levels of susceptibility. Susceptibility levels—usually four or five—are commonly mapped in diverging colour scale, with no general trend when it comes to the use of warmer or cooler colours for a specific end of the spectrum. It is common for studies presenting flood susceptibility assessments to map their results within a study area that is completely isolated from the broader geographical context, with no indication of the surroundings or of relevant geographical features or infrastructure in the region.

5.5. Sector-Specific Assessments

Some articles adopted a specific receptor-related perspective, dealing with an individual socio-economic sector to assess the impact and consequences of coastal flooding. Most of these works dealt with the potential impacts of coastal flooding on the transportation sector, which was mentioned to be a well-established field of research [102]. These studies aimed to identify the most critical portions of the transport infrastructure—with bridges being a prominent instance thereof—whose failure during storms and coastal flooding events might result in traffic disruptions, thus being crucial for the resiliency of the coastal system [102,192–194]. In general, this field of analysed research highlighted the need for achieving a certain level of redundancy and adaptation of the coping strategies between emergency and non-emergency measures in a dynamic way to better address the challenges of coastal flooding to the sector [192]. In an ex post analysis of the evacuation plan that had been disposed for Hurricane Irma in 2017, Huang et al. [195] highlighted that even though on that occasion the evacuation was completed successfully before the hurricane made landfall, the overestimation of the potentially affected population due to uncertainties in hurricane real-time forecasts caused traffic congestion and gasoline shortages. This work further stresses the critical importance of EWSs and information communication for the correct management of traffic during emergencies.

Flood assessments related to the transportation sector were often carried out with a combination of flood hazard modelling for the identification of the potentially flooded area with methodologies in the fields of network theory for the identification of critical nodes of the transport network. Similarly, other studies utilised alike methodologies to estimate potential disruptions and evaluate the resilience of the logistical and distribution sectors (e.g., portal infrastructure [196]) and other critical sectors (e.g., electricity systems, sewage network [197]) to coastal floods, sometimes also considering the cascade effects of disruption propagation from infrastructure and sectors directly affected by the flood to all other economic sectors within a wider area (e.g., [118] for a case study in the Caribbean island of Saint Lucia).

5.6. Tsunami-Driven Inundation

Tsunami-driven inundation constitutes a marginal interest of this review, insofar as it represents an example of rapid-onset coastal flooding which may require similar considerations in terms of both modelling, mapping and risk management. Tsunamis have historically been addressed differently the in literature when compared to other natural hazards [198], which might skew the contents of the reviewed literature. This work highlights that, for datasets identified using a search string related to coastal flood modelling and mapping (Table 2) and subsequently selected according to the data selection criteria summarised in Table 1, tsunami-related works represented only a small proportion (roughly 12%) of the final set of articles. The reader is referred to the Supplementary Materials for a list of which articles on tsunami-driven flooding were retrieved for this work, and to other relevant research (e.g., [198]) for more information on tsunami modelling.

6. Policy Implications

The issue of the function of the study in terms of its serviceability for policymaking and coastal management was actively addressed in some of the reviewed articles. While pondering the choice of appropriate tools in terms of the detail level and context-specificity of the provided information, Halsnæs et al. [94] emphasised the value of utilising localised data on flooding and costs even in light of the advantages in terms of methodological consistency of standardised methodologies or datasets. With respect to the scale of analysis utilised, Fahad et al. [78] highlighted that micro and macro assessments refer to different recipient segments, and emphasised the role and value of macro-level assessments when it comes to identifying priority regions and allocating resources. Similarly, Agharroud [106] emphasised the importance of the identification of hot spots to better define priority measures and aid in the implementation phase of coastal planning in the context of Integrated Coastal Zone Management (ICZM).

The issue of contrasting options faced during the decision making process was also addressed in studies that included different choice portfolios and master plans among the modelled scenarios considered [172]. In some studies, the authors worked specifically on tailoring the provided information to user needs. For instance, Idier et al. [152] proposed a user-oriented approach to the definition of the output of the analysis, whereby they asked what type of information was needed and then deployed a surrogate ML model to emulate indicators originally obtained as an aggregation of information from numerical models, also mentioning some of the feedback received. Other articles focused instead on the development of decision support tools (DST) such as web-based platforms for the simulation and visualisation of different scenarios of coastal flooding and adaptation [87,116,120,152].

Previous research has shown that representing and understanding complex problems and high-dimensional datasets of relevant climate variables is not straightforward [199], and this is also linked to risk perception. Interesting insights on risk perception—not necessarily only for policymakers or stakeholders, but also for the general population—were provided by [174,175], which showed a generalised underestimation of coastal flood risk in residents of coastal areas, and concluded that preventive action should take into consideration the tendency to underestimate areas exposed to flooding. On a similar note, other studies addressed the consequences of the potentially skewed risk perception on coastal management decisions: Bruno et al. [107] compared the risk of coastal floods as perceived by policymakers and stakeholders to physical risk, highlighting that risk perception can play a key role in shaping policy decisions and therefore should be taken into account to improve the effectiveness of coastal management.

The reviewed articles usually addressed the possible local adaptation measures for coastal flooding without going into too much detail about it. Those who did addressed both hazard-influencing measures and vulnerability-influencing measures [172]. The former usually entailed structural modifications of the coastal environment, and were sometimes included among the modelled scenarios considered, framing them as variations of the pathway or receptor. Variable combinations of grey and green infrastructure were proposed, such as mixes of the coastal defence structure with the replenishment of coastal ecosystems such as wetlands, vegetation and dunes [88,106,200]. Pertaining to grey infrastructure exclusively, some articles referred to the construction or modification—including retrofitting [40]—of coastal protection infrastructure such as drainage networks [41] and dikes [158]. Others focused on modifications to other types of infrastructure (e.g., the transport network [192]) to improve its resilience in the face of flooding events.

Some authors focused on green measures and the role of vegetation [25,73] or other natural features for the protection of the coast from storm events.

Coastal protection infrastructure was also addressed in terms of the assessment of the best logistical strategy to maximise its protection potential (e.g., establishing the best operating strategy for tide gates to mitigate the effects of storm surge [51]). Other articles mentioned the effectiveness of adaptation measures originally intended for another purpose; for instance, Khan et al. [201] assessed the storm surge reduction potential of land reclamation practices originally carried out in tidal zones for agricultural purposes.

A non-negligible portion of articles analysed the effects of non-structural measures [145,171] aimed at reducing vulnerability by increasing local adaptive capacity. The complexity and fragmentation of multilevel and multi-sectoral governance have been identified as relevant obstacles to the management of coastal coastal risks [107]. Within this context, multiple studies stressed the importance of establishing and maintaining communication channels among different stakeholders involved in the local coastal risk management [171], and of streamlining decision chains, reducing the responsibility fragmentation and creating integrated coastal masterplans to increase coastal safety [172].

7. Discussion and Conclusions

This review delineated the state-of-the-art of the literature regarding the modelling and mapping of rapid-onset coastal flooding, which are essential instruments for flood risk prevention and preparedness and are necessary to inform better policies for the resilience of coastal communities in the face of climate change.

Reviewed studies addressed different components of the DSPRC framework for the study of coastal flood systems, with a broad spectrum of methodologies. A generalised effort towards the development of rapid yet reliable flood assessment methodologies was noticed regardless of the disciplinary field, aimed especially to support flood EWSs and emergency responses.

The high level of uncertainty caused by the simplifications that are necessary to quantify the vulnerability of human and natural assets was among the most recurrent study limitations discussed by authors [82]. On a similar note, multiple studies emphasised the uncertainty embedded in well-established and widely used flood hazard and damage datasets, which might be particularly relevant for some coastal areas and lead to the underestimation of flood risk [36,44,159,202]. Issues pertaining to data availability and quality are of particular relevance for flood research [45] and were reported by numerous reviewed articles and across a broad range of geographical areas. This was observed for all types of data considered in the literature, including topographic and bathymetric datasets, observational wind and pressure fields—especially relevant for some particularly affected areas such as the Bay of Bengal [201,203]—and data needed for the characterisation of exposure such as census and infrastructure data [78,158].

Previous research emphasised the shortcomings in the description of the complex relationships among hydrodynamics, structural characteristics and community preparedness that determine the overall resilience of a community to floods [78]. Therefore, this review combined a broad scope in terms of adopted methodologies with stricter criteria for the type of spatial representation of floods to review studies conveying some level of information about the natural flooding processes, along with the local socio-economic indicators that are most commonly represented in the literature dealing with flood vulnerability and risk [186].

The results of this work highlighted that most of the articles selected based on these criteria focused exclusively on flood hazard, while only a residual portion of the analysed literature adopted broader perspectives encompassing flood vulnerability, risk and susceptibility. Even though different research products might be required to support different phases of the risk management process and diverse localised needs [78,202], the findings of this study emphasised the generalised lack of integration between studies focusing on the natural processes leading to flooding and those addressing the socio-economic characteristics contributing to vulnerability. On a related note, this review substantiated findings of extensive previous research on inconsistencies in the definition and operationalisation of most of the basic concepts related to the relationship between human and natural systems in the context of natural hazards. The unclear definitions of risk and vulnerability found a corresponding inconsistent translation in their spatial representation; this may require that these issues be more carefully addressed by the scientific community as they can represent a hindrance to an accessible application of research outputs to support climate adaptation policies.

The findings of this systematic review point to several promising directions for future research in coastal flood modelling and mapping. Future research efforts should focus on improving the representation of feedback mechanisms among the different components of a coastal flood system. This includes investigations pertaining to the relationship between different—potentially compound—coastal flooding sources and morphological changes, particularly in urban environments. Another relevant aspect to be studied in this area relates to the more accurate representation of the morphology of natural and man-made coastal structures in hydrodynamic models, and the quantification of uncertainty in the possible propagation of water inland.

Further attention is required to translate scientific advances into operational flood forecasting systems. The challenges of translating scientific research results into practical policy actions analysed in this paper relate specifically to climate change adaptation and resilience policies in coastal zones. However, the same challenges can be found at the research–policy interface more generally. The literature on this topic [204] has identified issues such as fragmentation in knowledge generation and sharing, more effective communication of research through face-to-face interactions between researchers and policy-makers, and the existence of trusting relationships between the two as some of the main reasons for these communication and practical difficulties. Future research developments could focus on the other complementary aspect of the research presented here, i.e., how different modelling and mapping results are used in practice from a policy perspective. On this note, focusing on the spatial representation of floods and other climate-related stressors is closely linked to the utilisation of vulnerability assessments for policies or practices envisioned by researchers, though the actual uptake of such assessments by practitioners remains an open question, as highlighted in previous research [205]. The role of local communities, policymakers or other stakeholders in utilizing flood maps is another fundamental aspect of research that might require investigation in future research. Therefore, future research should address the development of robust uncertainty quantification methods suitable for operational implementation, including the communication of these uncertainties to end-users. Finally, the standardization of flood mapping products and modelling approaches represents an important direction for future work. This includes evaluating the development of widely accepted protocols for model validation and uncertainty communication and standardised methods for incorporating new data sources and modelling techniques into existing flood risk assessment frameworks.

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