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An Overview of Flood Management from a Mathematical Perspective

REVIEW PAPER

ABSTRACT

Floods are among the world's most devastating natural disasters, resulting in loss of life, damage to property, and widespread infrastructure disruptions that impact millions. Flood modelling is a crucial tool for forecasting and effectively mitigating the consequences of such disasters. This study offers an overview of flood management strategies such as structural and non-structural strategies, and the current state of flood modelling, the challenges it faces, and potential future advancements. The scope of flood modelling encompasses various approaches, such as hydrological and hydraulic models, numerical simulations, rainfall-runoff analysis, remote sensing and geographic information systems (GIS), computational intelligence and robotics. The assessment delves into some of the merits and demerits of different models used to forecast the trajectory and consequences of flood events. This study explores the potential avenues for progress and innovation within the realm of flood modelling, including the integration of modern technology and multifaceted models. To enhance the control of flood hazards and reduce the societal influence of floods, the report underscores the imperative need for continuous research in the field of flood management through conventional and mathematical modelling.

Keywords: *structural strategies, non-structural strategies, flood modelling, hydrologic, hydraulic stochastic models*

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INTRODUCTION

Flooding poses a significant global challenge, affecting numerous urban areas and municipalities across developed and developing nations (*Hossain and Meng 2020; Rosmadi et al. 2023*). Analyzing future flood risks through predictive modelling suggests that the growing influence of climate change, coupled with inadequate readiness in numerous global regions for flooding incidents, may lead to unprecedented levels of damage caused by floods (*Pal et al. 2022*). The increasing occurrences of floods worldwide, according to *Hossain and Meng* (*2020*) and *Willumsen et al.* (*2019*), underscore the urgency of finding effective strategies for disaster risk management. Loss of infrastructure, human lives, agricultural yields, and commercial resources can be attributed to flooding events (*Atanga and Tankpa 2021*). *Wahlstrom and Guha-Sapir* (*2015*) reported that between 1995 and 2015, floods were responsible for 47% of all disasters related to weather, impacting a staggering 2.3 billion individuals with the vast majority, or 95%, residing in Asia. The rise in flood occurrences can be attributed to a combination of growing population and the impact of climate change (*Swain et al.2020*). Both elements are considered essential for comprehending the occurrence of floods. Built environment in littoral zones and catchment areas susceptible from flooding are more at risk due to continuous development (*Safiah Yusmah 2020; Witherow et al. 2018*).

Floods have the potential to inflict enduring consequences on the health and well-being of populations (*Grigorieva and Livenets 2022*) caused by potential presence ofhazardous chemicals and microorganisms in floodwaters. Population displacement resulting from flooding, along with the loss of homes, employment, and assets, may contribute to heightened poverty and social instability. Additionally, flooding can have indirect repercussions that are just as detrimental as the direct consequences. For example, supply chains and transport systems are disrupted, leading to increased prices for services and goods and a slowdown in commercial activities (*Pregnolato et al. 2017*). Furthermore, it gives rise to soil erosion, which has the potential to diminish agricultural output and result in the depletion of valuable arable land (*Chinnasamy et al. 2020*). Traffic interruption is an indirect damage of flooding that is more prevalent in the urban areas (*Zhou et al. 2022*). *Pyatkova et al.* (*2019*) highlighted that indirect impacts affect a broader area and are prolonged.

Floods can be triggered by various factors. The overflow of rivers into floodplains, often caused by natural phenomena such as hurricanes, weather systems and snowmelt, is a common cause of flooding. In addition, tsunamis and coastal flooding triggered by seabed earthquakes and lunar tides contribute to natural flooding (*Glago 2021*). Human activities also play an important role in the occurrence of floods. Urbanisation has become an important factor, especially in cities (*Zhang et al. 2018*). If the catchment area of a river is located in an urban area, the probability of flooding increases. In some areas, inadequate urban drainage systems are a major culprit, while in other areas poor management of drainage systems exacerbates the problem. Unplanned urban development is one of the main causes of flooding especially in many developing countries (*Ahmad and Moeeni 2019*).

Flood modelling performs a crucial role in understanding and predicting the behaviour and consequences of floods (*Nikoo et al. 2016*). To effectively anticipate where and when floods might occur, as well as the resulting damages and associated risks, it is essential to create mathematical models that represent the hydrologic and hydrostatic system leading to inundation (*Gori et al. 2019*) used in flood forecasting (*Wu et al. 2019*), risk assessment (*Psomiadis et al. 2021*), flood mitigation (*Su and Tung 2014*), and response planning and management. Several recent prominent scholarly contributions to the area of flood modelling include 1D (one-dimensional) hydraulic models (*Bessar et al. 2020*), 2D (two-dimensional) hydraulic models (*Senior et al. 2022*), and hydrologic models (*Clark et al. 2021*), to name a few. The 1D hydraulic models, which are grounded in hydraulic engineering principles, simulate movement of water in streams and channels. They are commonly used to predict the effects of flood management structures such as levees and dams and to forecast flood events. Nevertheless, even with their simplicity and user-friendly nature, 1D hydraulic models might not comprehensively depict the intricate interrelationships between floodwaters and the surrounding environment (*Pinos et al. 2019*).

In contrast, 2D hydraulic models depict the length wise and transverse movement of water and provide more detailed information on how the floodwater is distributed and what impact it has on the surrounding areas. These models not only depict the geographical and land tenure characteristics of the locality but also illustrate how floodwaters relate with their environment, including the impacts of urban development and plant cover (*Hankin et al. 2019*). These models can be based on phenomenon-based approaches (*Perez et al. 2019*), such as the distributed hydrologic model (*Dembélé et al. 2020*), or empirical methods (*Chu et al. 2019*) like the rainfall-runoff relationship. Hydrologic models are utilized to estimate the quantity and timing of runoff from catchment areas, which can be instrumental in creating flood predictions and warnings (*Hapuarachchi et al. 2022*).

The aim of this study is to synthesize the existing knowledge on the different flood management strategies using conventional engineering method and mathematical models, as well as stating the associated advantages and disadvantages through a systematic review of literature. Currently, there are various systematic reviews on flood management adopting mathematical models (*van Kalken and Havnø 1992; Jha and Gundimeda 2019; Kumar et al. 2023*). There is also extensive literature on flood protection and management approaches, .like flood vulnerability integrating geographic information system-based (GIS), legal systems of flood risk management, architectural flood defense, sustainable urban drainage systems (SUDS), natural infrastructure, green infrastructure, and nature-based solutions solutions (*Bellos and Tsakiris 2016; van Doorn-Hoekveld, 2017*).

This review article makes used a thorough examination of the various flood modelling methods. It includes hydrological, hydraulic, remote sensing, numerical, rainfall–runoff and artificial intelligence (AI) models. Rather than focusing on one aspect, it furnishes scholars with integrated analysis of the field so that they can explore and understand the advantages and disadvantages linked to each type of modelling. By bringing together these distinctive facts, the overview promotes a thorough knowledge of conventional flood management and the use mathematical modelling techniques and thus, aiding in well-informed policy making and the formulation of successful flood management systems.

MATERIALS AND METHODS

The research review on flood management techniques and mathematical models in managing flood in the ecosystems was conducted via thorough examination of the existing literature from 2010 to 2023, with the most recent systematic search conducted between January 2022 and November 2023. The primary emphasis revolved around flood management techniques (structural and non-structural) and flood modelling techniques. To gather enough relevant articles on the subject matter, databases including Google Scholar, Science Direct, Scopus, and Web of Science were systematically explored. The search query used keywords such as Environmental Science (natural flood disasters or flood management strategies OR flood modelling) and Mathematics (modelling and simulation OR mathematics (miscellaneous)) to retrieve the papers from these data bases. Sorted by Mendeley, a reference manager to remove duplicates, a total of 150 peer-reviewed publications were initially identified based on their relevance to the research topic. Following a detailed assessment of their titles and abstracts using content analysis, this pool was narrowed down to 120 publications.

Natural Flood Management Strategies

Natural flood management mitigates the potential for overflow and washing away of the littoral zones by safeguarding, rejuvenating, and imitating the innate roles of catchment areas, coastal plains, streams, and coastal regions. Watersheds are regions of the earth that gather rainfall and runoff water. Floodplains are level expanses adjacent to rivers, shaped by sediment deposits carried by the river, and they become inundated when the river reaches its capacity. The river topography has undergone significant transformations from its authentic crude state. Wetlands have diminished while hard surfaces have increased, leading to accelerated water runoff in river channels. This reduction in available space for water flow, coupled with the faster accumulation of water, has rendered rivers less resilient to cope with rising water levels, making flooding events more likely (*Lashford et al. 2022*).

Natural flood management employs techniques like enhancing temporary storage that can capture excess river water and release it gradually through measures such as reestablishing river-floodplain connections and constructing storage ponds. Additionally, it aims to decelerate water flow by restoring the sinuous course of rivers and bolstering antagonism to arise and in-channel water outpour by growing trees and foliage. Extending the zones where water can seep into the ground by improving soil quality and mitigating soil compaction performs a vital function in flood management (*Serra-Llobet et al. 2022*).

Flood Management Approaches are typically categorized into two main methods: structural and non-structural strategies. The choice between these methods depends on the specific circumstances, and each approach comes with its own set of strengths and weaknesses (*Ogie et al. 2020*).

Structural Strategies

Different types of structural strategies are used in the management and control of floods (**Table 1**). These are based on significant structural efforts to mitigate flooding based on technology, concrete and construction equipment. In this approach, synthetic systems are used to disrupt, block or minimise the effects of river procedures. Meanwhile, there are also advantages and disadvantages of structural strategies in the management of floods (**Table 2**).

Table 1. Types of structural strategies.

Technique	Explication
Dams	Earthen dams are massive infrastructure projects constructed across river channels to regulate the flow of water. Typically, they impound water behind the dam to create a reservoir that can be managed in terms of discharge, particularly during periods of excessive rainfall. Dams also serve as a source of hydroelectric power generation (*Kandlof and Yi 2022*).
Levees	Levees are elevated embankments, either naturally occurring or man-made, constructed along riverbanks. Man-made levees serve to prevent river flooding by diverting and containing floodwaters, thus protecting the surrounding areas. (*Mohd Nordin and Mohamad 2019*).
Channel straightening and deepening	Straightening river course is done to accelerate the gushing of water in flood-prone areas and to minimize water buildup in vulnerable regions. Additionally, deepening river channels increases their capacity to transport more water. (*Heritage and Entwistle 2020*).
Diversion spillway	Spillways are man-made channels designed to divert excess water when the rivers' release, i.e., the magnitude of water streaming via the river canal, increases. These channels divert water away from flood-prone areas and move it downstream or into another river. The installation of floodgates in spillways enables precise control of the volume of water discharged (*Flatley et al. 2018*).

Table 2. Advantages and disadvantages of structural strategies.

Type	Description	Advantages	Disadvantages
Sea wall	Barriers constructed along the shoreline using materials such as concrete, steel, or stone	1. Acts as a wall to avert flooding and erosion 2. Sea barriers can be employed as promenades	1. Over time, forceful waves can cause erosion to the walls 2. Costly
Groynes	Structures constructed from wood or rock and positioned perpendicular to the sea	1. Halt the occurrence of longshore drift 2. Builds up the beach over time	1. May deprive beaches farther down the coastline of essential resources 2. Difficult to walk along the beach
Riprap	Placement of substantial boulders at the base of a cliff or seawall.	1. Absorb wave energy and mitigate erosion, serving as a more cost-effective hard engineering method	1. Costly to transport and execute 2. Appear distinct from the local geological features
Gabions	Mesh cages containing rocks employed to mitigate erosion	1. Economical to manufacture and capable of absorbing wave energy	1. Easily damage by strong waves 2. Looks unnatural

Non-structural Strategies

This strategy utilizes techniques that require minimal civil works and focuses on flood prevention rather than flood control (**Table 3**). It utilizes the natural environment of rivers and works with the river's inherent processes. Non-structural strategies are generally more environmentally sustainable compared to structural approaches (*Ogie et al. 2020*). These adopted non-structural strategies have advantages and disadvantages in the management and control of floods (**Table 4**).

Coastal Flood Management

Littoral overflow control sets itself apart from river overflow control by its concentration on addressing flooding and erosion caused by the sea in a particular coastal zone. Nevertheless, both structural and non-structural methods perform a significant role in coastal flood control. Some examples ofstructural and non-structural approaches in seaside overflow management were explored by *Esteves* (*2014*) to investigate deeper into this topic.

Structural and Non Structural Strategies in Coastal Flood Management

Structural strategies employed in the management and coastal floods involves the construction of man-made structures to prevent the ingress of seawater into coastal regions and to mitigate coastal erosion (**Table 5**). Non-structural strategies function with the seaside as it is via repairing and renewing the ecosystem that subsists. The non-structural methods used in the management of coastal flood areas (**Table 6**) have advantages and disadvantages of non-structural strategies (**Table 7**) (*Hino et al. 2017*).

Table 3. Non-structural strategies for flood management.

Method	Explanation
Floodplain zoning	Floodplain zoning involves regulating the development of areas around rivers to prevent potential flooding of houses and structures. This practice also safeguards floodplains from urbanization, which expands the available land for infiltration, consequently reducing surface runoff (*Modak and Kapuria 2020*).
Afforestation	The planting of trees within a drainage basin enhances trapping of water and reduces the discharge into the river, thereby contributing to improved environmental quality in the vicinity of the river. Although afforestation can mitigate flood risks, it cannot completely avert the occurrence of floods (*Shah et al. 2022*).
Wetland restoration	Wetlands encompass regions of land that are intermittently or consistently inundated with water, encompassing environments like marshes, swamps, and bogs. Wetland restoration involves modifying areas to facilitate the growth of wetlands. These restored wetlands function as natural sponges, adept at capturing and gradually discharging various types of water, including surface water, rainfall, groundwater, and floodwater (*Alikhani et al. 2021*).
Washlands	Washlands represent designated land zones designed to accommodate excess river water during periods of high discharge. Equipped with sluice gates, they facilitate controlled flooding of low-lying areas, thereby safeguarding other regions, like towns from the risk of inundation (*Webster et al. 2014*).

Table 4. Advantages and disadvantages of non-structural strategies of flood management.

Type	Description	Advantages	Disadvantages
Beach Nourishment	Expansion of the beach through the addition of sand and shingle	1. Augments the distance of wave travel, consequently minimizing erosion 2. Integrates seamlessly with the existing beach	1. The sediment must originate and be transported 2. Demands regular maintenance
Dune Regeneration	Creating and restoring sand dunes	1. Dunes create barriers and absorb wave energy 2. Provides flood protection	1. Create barrier to the beach
Beach Reprofiling	Redistributing the sediment on the beach to stabilise erosion	1. Less expensive and simple to execute 2. Reduces wave energy	1. Applicable only in places with low wave energy 2. Requires maintenance
Managed Retreat	Some places along the coastline are left to flood naturally	1. Natural processes restored 2. Encourages wetland and salt marsh formation for wildlife	1. Compensation for land and livelihood loss required 2. Agricultural land lost

Table 5. Structural strategies to prevent flood in coastal regions.

Example	Interpretation
Groynes	Groynes, whether constructed from wood or concrete and extending from the coastline into the sea, serve the purpose of absorbing wave energy, capturing sediment, and preventing sediment movement away from the beach due to longshore drift (*Black et al. 2020*).
Sea walls	Sea walls are constructed using solid concrete to act as protective barriers that thwart the intrusion of high tides and storm surges, thus averting inland flooding (*Hosseinzadeh et al. 2022*).
Breakwaters	Breakwaters are coastal structures constructed from concrete, stone, or natural rocky materials. They serve to dissipate the energy of incoming waves at a distance from the shore, thus reducing the force and momentum of the waves that eventually reach the beach (*Hosseinzadeh et al. 2021*).

Table 6. Non-structural strategies in coastal flood management.

Example	Interpretation
Beach nourishment	Beach nourishment involves replenishing sediment that has been eroded from the beach, and when combined with engineered structures, it can enhance the beach's natural appearance and provide protection against local flooding (*de Schipper et al. 2021*).
Dune regeneration	Dune rejuvenation uses dunes as natural walls to safeguard coastal communities from heightened surges and floods. Dunes take shape as dune vegetation captures wind-blown sand and are positioned beyond the reach of high tide (*Doody 2012*).
Cliff stabilisation	Cliff stabilization is a method employed to mitigate coastal cliff erosion, aiming to curtail erosion, prevent potential landslides, and minimize the risk of falling rocks. One approach involves altering the slope and introducing vegetation to the cliff's upper section (*Lee 2002*).

Mathematical Models for Flood Disaster Management

According to *Benfer et al.* (*2019*), a model serves as an abridge description of a real- system, with the ideal model being one that closely approximates reality while employing minimal parameters and complexity. Models primarily find application in forecasting system behaviour and gaining insights into diverse hydrologic phenomenon. A model comprises a range of variables that articulate the model's attributes. A runoff model, for instance, can be described as a collection of formulasdesigned to evaluate runoff by considering a variety of variables that describe the characteristics of a watershed. Models for flood disaster management have been explained here, to provide context to the next section following the editor's comment.

Stochastic Models

Stochastic models rely on flood frequency analysis,a method used to establish a connection between the magnitude of flood discharge and the probability of it reaching or surpassing a certain level within a given year, or in terms of its recurrence frequency and return period (*Devia et al. 2015; Filipova et al. 2019; Heidarpour et al. 2017*).

Table 7. Difference between structural and non-structural strategies for flood management.

Factors	Structural Strategies	Non-structural Strategies
Scale	Usually constructed on a larger or more extensive scale	Operations on a more limited or reduced scale
Cost	High construction and repair costs	More budget-friendly, yet demands regular maintenance
Coastal Protection	Offer brief yet efficient erosion protection	Provide more sustainable solutions for addressing beach erosion concerns
Visual Appeal	Highly conspicuous and disturbs the aesthetic harmony of the landscape	Integrates seamlessly with the coastal surroundings and appears natural
Hazard Risk	Poses potential risks to humans, such as the danger of falling onto rock armour	Poses reduced harm to both humans and animals
Environmental Impact	Has the potential to decrease sediment accumulation downstream and disturb ecosystems	Remodelling the coastline has the potential to disturb wildlife

Calculating floods associated with specific return periods is crucial for designing flood protection measures, evaluating flood-prone areas, and effectively managing regions affected by floods (*Svetlana et al. 2015*). Given the influence of climatic variations on flood occurrences, stochastic modelling has gained extensive usage in estimating the flood magnitude linked to a specified level of risk. (*Chow et al. 1988; Ionescu and Nistoran 2019; Nazari and Seo 2021*).

The genesis of flood frequency analysis can be traced back to the demand for data to ensure the secure and cost-effective strategy of engineering infrastructure. This includes systems responsible for managing flood discharge, like bridges, trenches, diversion canals, waterholes, and spillways, as well as structures intended to safeguard land and property from flooding, such as walls and barriers. Furthermore, this approach is presently employed for planning and for establishing land-use categories through flood zoning, taking vulnerability into account. Frequency analysis is typically employed in the context of peak discharges, whether they are instantaneous or averaged over a specific time period. This analysis is conducted using historical river flow data to evaluate the likelihood of future exceedance events. Typically, it assumes that there will be no physical alterations in the fundamental statistics due to variations in climate or changes in land tenure. A wide array of likelihood disbandment and interpolation or extrapolation strategies have been utilized for this purpose. There are two primary methods for choosing the flood data series when fitting a stochastic model to observed floods: one relies on the annual maximum flows (AMF) series, while the other utilizes the partial duration series of floods based on the probability density function (PDF) method (*Karim et al. 2017; Swetapadma and Ojha 2023*). The AMF series focuses on identifying the most severe flood event for each year, disregarding the possibility that in certain years, the highest flows might be lower than floods in other years. Consequently, this method overlooks the inclusion of substantial high flood events when estimating parameters. On the contrary, the PDF methodology takes into account all notable flood occurrences during its parameter estimation procedure, even if it extends well beyond the number of years for which flow data is available. *Swetapadma and Ojha* (*2023*) introduced a novel connection between the return period of the PDF and MAF series, assuming the independence of flood events. *Swetapadma and Ojha's* (*2023*) research involved the fitting and application of both General Extreme Value (GEV) and Generalized Pareto (GP) distributions for the analysis of flood events.The advantages and disadvantages of stochastic models are Monte Carlo Simulation (*Clare and Piggott 2022*), Regression Models, and Markov-Chain Models (**Table 8**) (*Bolker 2008; Rubinstein and Kroese 2016*).

Deterministic Models

Deterministic models typically draw from the physical attributes of elements that play a role in or impact the phenomenon being studied. These elements include characteristics of the catchment, channel geometry, and the intricate processes of rain drainage (*Devia et al. 2015; Filipova et al. 2019*). Research in flood dynamics has typically focused on various mathematical models, roughly classified into two categories: stochastic and deterministic prototypes. Stochastic prototypes involve overflow frequency investigations, which explore the connection between the extent of flood discharge and the likelihood of it occurring within a given year or its recurrence frequency, often expressed as a return period. In contrast, deterministic prototypes are primarily founded on the physical attributes of factors that play a role in or impact the situation under study, like the attributes of the catchment, track geometry, and the

Table 8. Advantages and disadvantages of stochastic models.

Advantages	Disadvantages
Improved decision-making and risk assessment	Assumptions and simplifications in modelling techniques
Flexibility and adaptability to changing market conditions	Uncertainty and inherent inaccuracies in predictive models
Enhanced portfolio performance and diversification	Dependence on historical data and potential biases
Better long-term financial planning and wealth preservation	Need for expertise and understanding of complex mathematics

rainwater drainage procedure.

Deterministic modelling, specifically in the context of flood routing, refers to a mathematical approach used to forecast how the characteristics of a flow wave, such as its size, speed, and shape, change over time. This modelling technique is applied to predict these changes in one or more locations along a watercourse, which could be a variety of water bodies like rivers, streams, reservoirs, estuaries, canals, discharge ditches, or storm sewers. The flow wave being analyzed can originate from various sources, including precipitation runoff, controlled releases from reservoirs, landslides into pools, or tidal influences. Surge routing can be categorized into different types, such as hydrologic (lumped), hydraulic (distributed), or a combination of both (hybrid) (*Kumar et al. 2023*). Deterministic and probabilistic modelling are often intertwined. Probabilistic modelling can be employed to generate deterministic scenarios by simulating multiple possibilities with varying probabilities of occurrence. These deterministic scenarios can then represent different outcomes: Worst-case: e.g., maximum potential losses, Best-case: e.g. minimum potential losses, which might be fully absorbable, and Most likely: e.g., the losses that are most likely to occur (*Thompson and Frazier 2014*). The example of deterministic model is Water Balance Model. However, this model has some strengths and weaknesses (**Table 9**).

Hydrologic Models

Hydrologic modelling is a process that involves applying the continuity equation to ensure a balance between the incoming water, outgoing water, and the volume of water stored within a given system (*Nazari and Seo 2021*). In addition to this, a secondary relationship called the storage-discharge relation is essential to explain how the rate of water outflow is connected to the capacity of the storage of the system. This modelling approach assumes that the water surface remains relatively constant along the watercourse, which is typically the case in scenarios like reservoirs or lakes. However, in more complex situations, for instance, scenarios encompassing elongated and slender pools or open canals, where reservoir is affected by both incoming and outgoing water, it becomes necessary to develop more intricate relationships. Numerous methods, encompassing graphical and mathematical approaches, have been suggested for addressing the continuity equation. Hydrologic modelling is preferred for its ease of use in contrast to hydraulic models. Nonetheless, it comes with constraints, as it does not accommodate backwater effects and may not precisely depict swiftly increasing hydrographs in gradually sloping rivers or extended reservoirs (*Ávila et al. 2022*). Furthermore, De *Wrachein and Mambretti* (*2015*) classified hydrological models into three types, namely level-pool types (reservoirs), storage types (applied to rivers) and linear systems (linear reservoirs).

Hydraulic Models

To comprehensively grasp the dynamics of an intricate flooding event, hydraulic models are indispensable. This is due to the fact that the flow rate, velocity, and depth exhibit spatial variations throughout the channels and over floodplains. These vital characteristics can be ascertained by applying the full pack of differential equations governing 1D or 2D unsteady flow, commonly referred to as the De Saint Venant (SV) or shallow water (SW) equations (*Kumar et al. 2023*). These equations enable the calculation of the speed of discharge and the level of water as procedures of both spatial and temporal, in contrast to lumped flow routing methods that rely solely on time. When these equations are applied for dispersed discharge routing, according to the entire SV or SW equations, it is referred to as hydrodynamic routing. In certain situations, these guiding equations

Table 9. Advantages and disadvantages of deterministic models.

Advantages	Disadvantages
Quick to simulate	Absence of intricate, detailed structure
Susceptible to mathematical analysis	Challenging to connect experimental data
Appropriate for systems comprising a large number of cells	Disregard the impact of randomness

can be abridged to a 1D continuity equation and a steady gush connection, which is known as kinematic wave routing. This simplification suggests that release can be determined as a straightforward process of deepness. An equilibrium between gravitational and frictional forces within the channel characterizes consistent flow. This hypothesis is often challenging to substantiate, particularly in situations involving extremely gentle slopes where the impact of the water surface cannot be disregarded. In such cases, additional factors come into play within the momentum equation for hydraulic routing (*de Wrachien et al. 2015*).

Hydraulic modelling takes into account the following factors, among others: The movement of the tides or storm surges in an upstream direction; the influence of downstream reservoirs and inflowing tributaries on the water level, leading to backwater effects; and hasty discharges from pools or dam breaches lead to sudden and turbulent waves. Similarly, the choice of a discharge routing prototype for a certain application is determined by emphasising the following factors: the suitability of the model to answer specific user queries; the precision and reliability of the model; the type and accessibility of the necessary data; and the degree of sophistication of the mathematical framework.

Dispersed discharge routing representatives prove valuable in assessing floodplain depths, determining the necessary elevations of structures like levees or bridges, creating flood maps for backup plans in case of dam breaks, analyzing transient waves resulting from gate or turbine operations in reservoirs, examining waves generated by landslides in pools, and studying unstable flow within storm sewer techniques. In each of these applications, the actual flow process exhibits variations in all three spatial dimensions (*de Wrachien et al. 2010*).

Hybrid Models

Hitherto, hydraulic samples were not regarded as a feasible option for surge routing due to the perceived economic impracticality of acquiring cross-sectional data for the extended sections involved in flood routing. Current research, however, has shown that hydraulic routing can be effectively applied to calculate release hydrographs in sections with limited canal geometry information by simplifying the sample to resemble a rectangular canal. It has been demonstrated that this "limited geometry" modelling procedure, using 1D Saint Venant equations, can reliably predict discharge hydrographs, establishing it as a practical and viable option for hydrologic overflow routing. Additionally, it has been discovered that this hybrid model presents the benefit of seamlessly integrating flood routing and the calculation of overflow levels, as noted by *Blackburn and Hicks* (*2002*). Furthermore, employing a hydraulic model also unlocks the capability to simulate additional active flood scenarios, like surges resulting from ice jam releases, which cannot be addressed using conventional hydrological modelling methods.

Subsequently, the overflow tide generated must be input into a hydraulic model that relies on comprehensive canal geometry data to predict overflow occurrences at critical locations. A novel deterministic procedure employs irregular discharge hydraulic modelling for both overflow routing and deluge level estimation. This mixed sample presents the operational benefit of seamlessly integrating flood routing with flood level estimation. Furthermore, this method introduces the potential to simulate more dynamic flood scenarios, including surges caused by ice jam releases, a challenge not addressed by conventional hydrologic or hydraulic modelling methods.

Moreover, this mixed model presents the additional benefit of smoothly incorporating flood routing and flood level estimation, as emphasized by *Blackburn and Hicks* (*2006*). Furthermore, the use of a hydraulic model extends the possibility of simulating better vibrant flood scenarios, including surges resulting from ice jam releases, which pose challenges beyond the capabilities of conventional hydrological modelling techniques. In empirical flood forecasting applications, there are typically two steps involved. In the initial stage, a flood routing model, typically of a hydrological nature, is used to estimate the peak flood flow by directing flood events between monitoring stations for streamflow. Subsequently, this flood wave is input into a hydraulic model that relies on precise canal geometry to predict overflow occurrences at critical locations. A novel deterministic method now utilizes unstable gush hydraulic modelling for both overflow routing and overflow level determination. This innovative hybrid model not only streamlines flood routing and flood level determination but also enables the modelling of more complex flood events, such as ice jam release surges, which were previously challenging to address using traditional hydrological or hydraulic modelling techniques.

Numerical Flood Modelling

Numerical flood models are computerized tools that utilize mathematical and computational methods to replicate the dynamics of water during an overflow occurrence (*Anees et al. 2016*). These samples commonly utilize numerical algorithms to address equations that depict water flow in rivers or streams, accounting for variables like precipitation, runoff, river channel dimensions, and the roughness of the riverbed. Numerical flood models can replicate the consequences of different flood situations and also evaluate the effectiveness of suggested flood control measures (*Saleh et al. 2013*). Furthermore, these models are employed to predict how flood patterns may adapt in reaction to alterations in weather, land use, and other determinants. Numerical overflow models can assume various structures, including one-dimensional models, which imitate water movement within a river channel (*Pramanik et al. 2010*), or 2D models, which recreate water flow across an alluvial plain (*Rameshwaran et al. 2007*). In the case of three-dimensional (3D) models of the alluvial plain, they provide a more intricate portrayal of the vertical distribution of water (*Marsooli et al. 2016*). Numerical flood models provide many benefits over physical floodmodels, such as the capacity to incorporate a greater volume of data and information and simulate complex hydrological and hydraulic processes (*Luo et al.2022; Pontes et al. 2017; Cozzolino et al. 2019*). Numerous software packages are accessible for numerical flood modelling (**Table 10**).

Out of the five software, HEC-RAS and EFDC are the free software offered to the public (**Table 11**). It is essential to emphasize that the selection of software should be based on the precise requirements of the study of overflows, as well as the accessibility of data and available resources. In their studies, *Shustikova et al.* (2019), *Schubert et al.* (*2022*), and *Chang et al.* (*2018*) conducted a comparative analysis of two 2D numerical models, namely LISFLOOD-FP and HEC-RAS, for floodplain flooding assessment. Their findings indicate that, while coarser grids yield similar results, employing higher-resolution grids leads to more favourable outcomes. Nevertheless, it is important to recognize that flood characteristics' geographical distribution can vary in different regions.

Furthermore, *David and Schmalz* (*2020*), as well as G*arcía-Alén et al.* (*2022*), conducted a comparative

Table 10. Software packages accessible for numerical flood modelling.

Software	Developed by	Application	Reference
HEC-RAS	US Army Corps of Engineers	1. Riverine floodplain modeling and analysis can be conducted 2. It is employed to evaluate the impacts of diverse floodplain management strategies 3. This tool is utilized to gauge how planned developments may influence floodplain conditions	(*Khattak et al. 2016; Kumar et al. 2023*)
MIKE FLOOD	Created by Danish Hydraulic Institute (DHI)	1. Suitable for both riverine and coastal floodplain modelling and analysis 2. Effective for assessing the consequences of various floodplain management approaches 3. Applicable for assessing the impacts of prospective outcomes on floodplain states	(*Tansar et al. 2020; Kumar et al. 2023*)
TUFLOW	WBM Pty Ltd and The University of Queensland	1. Applicable for modelling and analyzing floodplains in both riverine and coastal environments 2. Suitable for assessing the consequences of diverse floodplain management approaches 3. Valuable for evaluating the impacts of designed growths on floodplain states	(*Fahad et al. 2020; Kumar et al.,2023*)
Flood Estimation Handbook (FEH) models	United Kingdom Environment Agency	1. Suitable for conducting flood hazard assessments and creating floodplain maps in the United Kingdom 2. Valuable for aiding in floodplain management and facilitating decision-making processes in the UK regarding flooding	(*Faulkner and Wass 2005; Kumar et al. 2023*)
Environmental Protection Agency's Environmental Fluid Dynamics Code (EFDC)	United States Environmental Protection Agency	1. Applicable for modelling and analyzing riverine and coastal floodplains 2. Useful for assessing the effects of various floodplain management approaches 3. Valuable for assessing how proposed developments may affect floodplain conditions	(*Roy et al. 2020; Kumar et al. 2023*)

Table 11. Some advantages and disadvantages of numerical modelling software.

Model	Advantages	Disadvantages
HEC-RAS	1. An intuitive graphical interface for model creation and visualization 2. Prevalent and esteemed within the engineering field 3. The ability to simulate both stable and dynamic fluid flows	1. Its capacity to represent intricate shapes and boundary conditions is constrained 2.Handling extensive models or intricate simulations can demand significant computational resources. 3. Its capability to handle relations between water and the surrounding territory, like deposit movement, is restricted
MIKE FLOOD	1. An all-encompassing and adaptable flood analysis and forecasting instrument 2. Competent in addressing a wide spectrum of hydraulic and hydrological procedures 3. Seamlessly integrate with various MIKE software tools to deliver a more holistic solution	1. New users may encounter a significant learning curve 2. Handling large models or intricate simulations can demand substantial computational resources 3. Effectively utilizing it necessitates a high degree of technical proficiency
TUFLOW	1. An intuitive graphical interface for constructing and visualizing models, designed to be user-friendly 2. Capable of managing a broad spectrum of hydraulic and hydrological procedures 3. Versatile and adjustable to accommodate distinct modelling needs	1. Constrained in its capacity to manage extensive models or intricate simulations 2. Presents a challenging learning process for newcomers 3. Demands a significant level of technical proficiency for efficient utilization
Flood Estimation Handbook (FEH)	1. Universally recognized and extensively utilized in the United Kingdom 2. Offers a uniform and standardized method for estimating flood occurrences 3. Straightforward to utilize and configure	1. Constrained in its capacity to manage intricate models or simulations 2. Might not be appropriate for deployment in regions or nations with varying climatic and hydrological conditions 3. Its capability to factor in alterations in land tenure and ground cover over a period can be restricted
Environmental Protection Agency's Environmental Fluid Dynamics Code (EFDC)	1. An all-encompassing instrument for simulating diverse environmental processes, such as floods 2. Proficiency in managing intricate models and simulations 3. An intuitive user interface featuring graphical elements for constructing and visualizing models	1. New users may encounter a significant learning curve 2. Large models or complex simulations can demand substantial computational resources 3. Effectively utilizing it necessitates a high degree of technical proficiency

analysis between the conventional "decoupled" approach and an "integrated" technique to evaluate the hazards of floods in tiny rural communities. Their studies highlighted the advantages, disadvantages, and limitations of each method. *Costabile et al.* (*2021*) and *Fernández-Pato et al.* (*2016*) conducted a reference point study on the HEC-RAS 2D (HR2D) program for Rain-on-Grid (RoG) simulations, evaluating its suitability and constraints for assessing storm hazards in diverse scenarios. Similarly, *Zeiger and Hubbart* (*2021*), and *Cea and Bladé* (*2015*) assessed the effectiveness of an intermixed modelling approach for assessing environmental fluctuations by employing SWAT and HEC-RAS. Their findings showcased the production of naturalistic simulations and indicated the possible applications of 2D Rain-on-Grid HEC-RAS simulations.

Rainfall-Runoff Modelling Techniques

Rainfall-runoff samples are hydrological tools employed to activate how precipitation is transformed into runoff within a specific drainage area. These models have a critical function in forecasting the timing and volume of runoff within drainage, a fundamental aspect of proficient water resource management and flood prediction (*Moradkhani and Sorooshian 2008*). These models can be categorized into three main types: practical, ideational, and physical process-based samples (*Peel et al. 2020*) (**Table 12**). In particular, conceptual models, which replicate the process of runoff generation, simplify the hydrological cycle and utilize concepts like the water equilibrium equation and groundwater equilibrium. Conceptual models are valuable for anticipating catchment behaviour, especially when there is limited input data available, while still desiring a comprehensive knowledge of the hydrological procedures. Some

Table 12: Advantages and disadvantages of rainfall runoff models.

Model	Description	Advantage	Disadvantages
Conceptual Models	Using a simplified depiction of the water cycle as a basis	User-friendly, with a minimal requirement of input parameters, and effective in forecasting the behaviour of smaller to moderately-sized watersheds in cases where hydrological processes are well-understood	Might not provide a precise representation of the underlying physical runoff generation processes and has restricted capabilities in simulating the impacts of alterations in land use and climate
Physical Process-Based Models	Drawing from a comprehensive grasp of the underlying principles governing hydrological phenomena	Precisely depict the physical mechanisms responsible for runoff generation, facilitating the prediction of runoff in expansive watersheds and the simulation of intricate hydrological processes	Necessitates an extensive quantity of specific data and computational assets, which can make the setup and execution a laborious and intricate process. Furthermore, it may exhibit a susceptibility to inaccuracies in input data
Empirical Models	Derived from statistical correlations between rainfall inputs and observed runoff results	Streamlined and effective, relies solely on historical data for rainfall and runoff, making it valuable for flood prediction, urban drainage system design, and water resource management	It might not faithfully capture the underlying physical mechanisms governing runoff generation, possess constrained capability to replicate the impacts of alterations in land use and climatic conditions, and could exhibit suboptimal performance beyond the scope of the historical dataset used in model development

examples of conceptual models comprise the Bayesian networks (BNs), the HBV model, and the Nash cascade model (*Sahoo et al. 2020; Chen and Pollino 2012; Hlavcova et al. 2005*).

A comprehensive understanding of the underlying natural activities governing runoff production forms the basis for natural action-based models, which encompass factors such as permeability, evaporation, transpiration, and drainage routing. Even though these models demand substantial computational resources and accurate data input, they excel in accurately replicating catchment behaviour across a wide spectrum of hydrological states and prove invaluable in the simulation of intricate hydrological processes (*Fatichi et al. 2016*). One example of a physical process-based model is the Soil and Water Assessment Tool (SWAT) (*Arnold et al. 1998*), which models the hydrological processes within a watershed, encompassing aspects such as exterior runoff, groundwater recharge, and transportation of sediments (*Ramkar and Yadav, 2021; Barbero et al. 2022*). The MIKE SHE models (*Abbott et al. 1986*) is another example, focusing on the simulation of interactions between surface water and groundwater while considering variables like land use, soil characteristics, topography, and the appraisal of weather and impact of land use. WATFLOOD is yet another model that simulates various catchment hydrological operations, including floods, runoff, infiltration, recharge, and routing. It is especially useful for evaluating control techniques and assessing flood risk (*Kouwen 1988*).

Empirical models rely on statistical correlations between precipitation inputs and monitored runoff outputs. While these models may not capture the fundamental physical operations, they offer simplicity and minimal data requirements. Empirical models find extensive application in overflow prediction, metropolitan drainage planning, and water resources planning. Illustrations of empirical models encompass data-driven approaches like regression models (*Liu and Pender 2015*), artificial neural networks (*Kumar and Yadav 2020*), diverse engine learning algorithms, and the Soil Conservation Service Curve Number (SCS-CN) technique (*Mishra and Singh 2004*). Comprehensive reviews of practical, hydrodynamic, and ideational flood models, elucidating their advantages, limitations, and probable uses, were conducted by *Teng et al.* (*2017*) and *Buttinger-Kreuzhuber et al.* (*2022*). Similarly, *Maranzoni et al.* (*2023*) have conducted a comparative analysis of multiple procedures, factors at risk, and applications for the quantitative assessment of flood hazards. This comparative study offers valuable guidance on selecting the most appropriate evaluation techniques.

The preference for a specific rainfall-runoff model hinges on the purposes of the investigation, the availability of data, and the required level of complexity for accurately replicating hydrological processes (*Papaioannou et al. 2017*). The selection of model structures and associated factors significantly influences the performance of distributed hydrological models. Notably, model parameter uncertainty poses a substantial challenge, and computational time can be lengthy. Nonetheless, advancements in computer resources have opened up possibilities for improved performance through independent escalation, calibration-free models, and parallel techniques (*Li et al. 2017*). For probabilistic flood prediction using deterministic models, Bayesian systems offer a solid theoretical foundation (*Han and Coulibaly 2017*).

Remote Sensing and Geographic Information Systems (GIS)-Based Flood Models

Flood models are created through the merger of remote sensing and GIS mechanisms, which perform a critical function in storm forecast and flood control (*Sharma et al. 2023*). Remote sensing involves the collection of Earth's surface data from a stretch utilizing instruments like satellites and aircraft. GIS software is utilized for the management, analysis, and visualization of geographical information (*Kabenge et al. 2017*). By harnessing remotely perceived data and GIS tools, flood models can imitate the behaviour of water during an overflow event (*Sharma et al. 2021*). These models comprehensively examine and evaluate the geography, hydrology, meteorology, and the use of land in the research area, drawing data from diverse sources like satellite imagery, aerial photography, and ground-based observations (*Costache et al. 2019*).

The models can be applied to assess the efficacy of suggested flood prevention measures and simulate the potential outcomes of different flood scenarios (*Thakur et al. 2016; Mehta et al. 2022*). To illustrate, satellite imagery is utilized to chart the areas affected by floods and identify regions prone to flooding (*Skakun et al. 2014*). Digital elevation models (DEMs), derived from remote sensing data, are employed to construct overflow maps that predict which spots are susceptible to flooding in a specified flood occurrence (*Coveney et al. 2017*). GIS is employed to analyze the spatial correlations between various factors contributing to floods, such as ground use, soil types, and terrain (*Garcia-Ayllon and Radke 2021*). GIS is also employed to produce flood danger maps that depict the scope and profundity of potential flood inundation. Additionally, it aids in assessing flood risks and supporting decision-making processes related to flooding (*Saha and Agrawal 2020*; *Mangukiya et al. 2022*).

Remote sensing and GIS-based flood models offer several advantages compared to additional kinds of overflow models. These advantages include the flexibility to utilize a wide array of information and data sources, the capability to integrate diverse data classes into a unified framework, and the aid for spatial investigation and conception (*Muhadi et al. 2020*). However, they do come with certain drawbacks, such as the requirement for accurate and high-quality data, the prospect of mistakes and vagueness in the results, and the necessity for special ability and skills to develop and understand these models (*Sharma et al. 2020*). Diverse uses of remote sensing and GIS in the context of floods encompass scenarios like flash floods (*Ding et al. 2021*), urban areas impacted by floods (*Hermas et al. 2021*), flood risk assessment (*Thanh Son et al. 2022*), the development of flood risk indices (*Ramkar et al. 2021*), flood vulnerability mapping (*Mohamed and El-Raey 2020*), and the analysis of flood hazards (*Hong and Abdelkareem 2022*).

Overall, the key advancements of remote sensing and GIS-based flood models encompass the integration of diverse data sources, enhanced accuracy and timeliness, spatial analysis and visualization, scenario analysis and decision support, improved flood risk management, and accessibility and collaboration (**Table 13**). These novel aspects substantially increase the capability to predict, manage, and mitigate flood risks, leading to better preparedness and resilience towards floods, especially in flood-risk areas.

Flood Modelling Using Artificial Intelligence and Machine Learning

The field of flood modelling has recently witnessed a transformative development with the integration of AI and ML. This innovation holds the promise of reshaping the way we predict and manage floods (*Hou et al. 2021; Herath et al. 2023*). Through the application of AI and ML algorithms, vast datasets encompassing meteorological, hydrological, and topographical information are scrutinized, leading to enhanced precision and dependability in flood modelling. ML empowers these systems to refine their performance organically, devoid of the need for explicit programming (*Sarker et al. 2020; Rahim et al. 2023*). The methodologies of ML involve a learning process wherein the system endeavours to achieve a designated task by assimilating knowledge from prior experiences (*Liakos et al. 2018*). In assessing the effectiveness of an ML model in handling a specific assignment, an implementation metric is employed to

Table 13. Overview of remote sensing data types and their applications in the field of floods and water resources.

Type of remote sensing data	Characteristics	Uses
Optical Imagery (*Tripathi et al. 2020*)	Collects light in the visible and near-infrared spectrum	Classification of land cover, monitoring of vegetation, urban development planning, and mapping of floods
Thermal Imagery (*Moore and North 1974*)	Captures heat radiation	Detection and monitoring of floods, as well as the mapping of flood-affected areas
Radar Imagery (*Schumann et al. 2012*)	Utilizes radar waves to identify and gauge objects and topography	Topography mapping, coastal erosion monitoring, oil spill detection, and flood mapping
LiDAR (*Li et al. 2021*)	Utilizes laser pulses for distance measurement and the generation of 3D models	City development planning, mapping of flood-prone areas, and delineating flood boundaries
Hyperspectral Imagery	Grasps data across a broad spectrum of wavelengths	Monitoring the environment and mapping floods
Infrared Imagery (*Khan et al. 2018*)	Captures thermal radiation	Detecting and monitoring fires, assessing crop health, monitoring water resources, and mapping floods
Satellite Imagery (*Moore and North 1974*)	Acquires remote sensing data through sensors mounted on Earth-orbiting satellites	Weather monitoring, tracking changes in land use, observing natural disasters, and creating flood maps

optimize the learning process (*Janiesch et al. 2021; Chabokpour et al. 2020*). ML technology is classified into four classes according to the methods of education: supervised education, unsupervised education, semi-supervised education, and support education (*Mohammed et al. 2016*).

Karim et al. (*2023*) delved into the utilization of ML and deep learning (DL) algorithms for flood inundation modelling. DL models, while more precise, encounter challenges stemming from a shortage of expert knowledge and benchmark data. In the pursuit of real-time anticipation of fluvial floods, *Bomers and Hulscher* (*2023*) compared conceptual models with data-driven models, particularly focusing on neural networks, and highlighted both their advantages and drawbacks (**Table 14**). Hydrological modelling leverages supervised learning algorithms like Support Vector Machines (SVM) (*Singh et al. 2023*) and Artificial Neural Networks (ANN) (*Wang et al. 2017*), while the modelling of flood inundationmapping employs DL algorithms such as Convolutional Neural Networks (CNN) and other DL techniques (*Karim et al. 2023*). For the evaluation of flood risk, early warning systems, and flood damage, decision trees (DT), Random Forest (RF), and other ML algorithms are employed (*Pham et al. 2021; Wang et al. 2015*)

Artificial intelligence and ML offer useful yet advanced. automated data-driven approaches for flood modelling, furnishing enhanced prediction accuracy, efficiency, and actionable insights. As technology advances and more data becomes available, these methods

Table 14. A summary of various AI and ML techniques applied in the flood modelling.

Flood modelling	Artificial intelligence (AI) and machine learning (ML)
Hydrological Modelling	Artificial Neural Networks (ANNs), Support Vector Machines (SVMs), and various other supervised learning algorithms are applied for modelling complex hydrological phenomena and predicting occurrences of flooding (*Xie et al. 2021*).
Flood Inundation Mapping	Employing Convolutional Neural Networks (CNNs) and other advanced deep learning algorithms, we can create inundation maps for areas affected by floods by utilizing high-resolution remote sensing data, including satellite imagery and aerial photos (*Andrew et al. 2023; Zakaria et al. 2019*).
Early Warning Systems	Artificial Neural Networks (ANNs) and various other machine learning (ML) algorithms are harnessed to develop early warning systems that provide real-time notifications derived from predictions of potential flood events and their potential consequences (*Ahmad et al. 2022*).
Flood Damage Assessment	The potential damage caused by flood disasters has been evaluated utilizing Decision Trees (DT), Random Forest (RF), and other machine learning (ML) methodologies (*Seydi et al. 2022*).

will continue to evolve, providing even greater potential for effectual flood management and risk mitigation.

CONCLUSION

Utilizing mathematical models in conjunction with other strategies to address water management issues provides valuable prospects for formulating a range of measures capable of mitigating flood damages to an acceptable extent. The modelling approach stands out as the most effective tool for assessing the efficacy of various options across a spectrum of potential flood events and selecting the optimal alternative. This assessment will be beneficial for academics, practitioners, and decision-makers in their efforts to develop more precise and reliable flood models and risk management strategies.

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