

Systematic review of hydrodynamic models used in flooding simulation under Climate Change scenarios

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Abstract

The present research focuses on a systematic review of Hydrodynamic Models used during the fluvial, pluvial and coastal flood simulation under climate change scenarios worldwide. Research selection and retrieval criteria were defined, taking into account the thematic focus, which were critically evaluated. The selection of hydrodynamic models for flood modeling depends on key aspects such as, environmental and climatic conditions, behavior of variables in water bodies, and new parameters are included, which become key factor during the modeling. HEC-RAS and MIKEFLOOD are among the most widely used models, due to their capacity and efficiency in flood modeling and reflect accurate results. However, other models are used, which despite not being recognized, they have modeling capabilities and exhibit a solid vision about the coastal, pluvial and fluvial floods under the near future. They are the basis for decision making associated with climate adaptation and risk prevention. It is the first review that covers this horizon in flood hydrodynamic modelling, since there is no evidence of documentary exploration of the subject.

Keywords *Hydrodynamic modelling, inundation, climate change and hydric resource.*

Introduction

Climate change has created social and global ecological impacts on water resources, environment and fluvial, pluvial and coastal flood risk (Gaeta et al., 2018). As a consequence of Climate Change, floods will be influenced by water levels increasing and alteration in precipitation patterns, which leads to the occurrence of extreme rainfall events, due to increase in water saturation concentrations for each degree of temperature augmented (Pasquier et al., 2019; Tabari, 2020).

Climate change impacts on floods is evidenced by the research conducted by AlZaatiti et al., (2025) in Lebanon, where it will promote extreme climate and changes in the area flooding and hydrology. It affects million populations and natural ecosystems. Furthermore, Munar et al., (2023) stated that in South America, Magdalena Basin has undergone alterations in fluvial discharge and flood extend due to Climate Change, which promotes loss in vegetation cover and freshwater fish. Xu et al., (2023) affirm Haidian Island, China is going to undertake rainfall raising, which amplifies jacking effect of the SLR, volume, depth increase and flood duration in areas near the outfall.

The development of tools and models to represent flood and dynamic changes is crucial for projecting them under Climate Change scenarios and future periods. Hydrodynamic modeling, that is used to understand fluid movements and floods dynamics, under dimensional methods has capabilities and outputs to support the pluvial, fluvial and coastal flooding risk management under Climate Change scenarios and decision making (Gaeta et al., 2018). It is based on solving equations derived from physical laws of fluid motion, under different complex degrees. Therefore, during the hydrodynamic modeling is important to consider new variables on the waterways such as, maximum water level-precipitation, land use and time-space scales, to assess the impacts of this phenomenon with precision and low levels of uncertainty (Pasquier et al., 2019; Teng et al., 2017).

Intergovernmental Panel on Climate Change (IPCC) created Climate Change Projections and future scenarios based on global temperature and precipitation increasing, greenhouse (GEI) emissions, atmosphere changes and ocean under future short-, medium- and long-term periods (IPCC, 2019). They have been used by authors to quantify future changes in flood events in areas with an occurrence history of extreme events mainly (Bhusal

et al., 2025; Gaeta et al., 2018; Pasquier et al., 2019). The most commonly used are Global Circulation Model (GCM) (Hsiao et al., 2021; Mohanty & Simonovic, 2021; Try et al., 2025), which considers global climate, Regional Climate Model (RCM) (Hosseinzadehtalaei et al., 2021; Mahato et al., 2022), that takes into account climate in specific zone with Representative Concentration Roads (RCP) (Gusain et al., 2020; Triet et al., 2020), and Share Socio Economic Pathways (SSP).

It is evident that hydrodynamic models are used in several investigations for flood simulation, considering key variables, under different context, climate Change scenarios and future periods. Nevertheless, these researches are scattered and have not been systematized to disseminate their efficiency and application to model under environments with similar characteristics, as well as update contents at the academic level. It is for this reason that the purpose of the article is to perform a systematic review of hydrodynamic models used to simulate coastal, fluvial and pluvial flooding under Climate Change scenarios worldwide to provide knowledge and showcase information about the current state of art in this area, which can be the basis for investigations associated with floods. It is the first review that covers this horizon in flood hydrodynamic modelling, since there is no evidence of documentary exploration of the subject.

Methodology

The article presents an analysis of the researches used during the review, which have been selected according to defined criteria to encompass the context. A search of scientific production was carried out in databases of high academic relevance such as, Science Direct, Scopus, Springer, Web of Science and Google Scholar, based on defined selection criteria: keywords which were “Hydrodynamic modelling, flooding and climate change”; publication year (2019-2025), type of document (Research article) and language (English). Information retrieval was carried out using Boolean Operator Model “and” to narrow the search and find research articles, which contain key words defined previously and connected by the operator. In this way, researches were filtered efficiently and the direct review was minimized.

Research articles found was reviewed and analyzed briefly, considering the use of hydrodynamic models in different fields under Climate Change scenarios. 80 articles were compiled, which Climate Change scenarios selected to simulate, flood and hydrodynamic model type, variables involved during the modelling and results obtained from the research was critically evaluated. The results obtained are presented below, as well as, the strengths and weakness of the main models used to simulate under Climate Change scenarios.

Article development

Hydrodynamic modelling of pluvial, fluvial and coastal floods under Climate Change scenarios uses diverse numeric models, which are selected according to the current context, climate conditions and model efficiency of key parameters to describe flooding behavior and evaluate its impact under selected scenarios. One of the most widely used model is HEC-RAS (1D-2D), due to its efficiency in fluvial, pluvial and coastal floods modelling under 1D-2D and coupled domain. Several investigations applied HEC-RAS (1D) to evaluate Climate Change (CC) impacts under fluvial flooding (Kiran et al., 2023; Mahato et al., 2022; Modi et al., 2022), changes in hydrodynamic estuaries characteristics (Krylenko et al., 2025; Sarchani & Tsanis, 2024), flooding extend (Aryal et al., 2022; Dysarz et al., 2024; Edamo et al., 2022), frequency (Aryal et al., 2022) and depth dynamics (Edamo et al., 2023; Sarchani & Tsanis, 2024) in risk zones.

Flood modeling is applied under different time periods, project climate models and scenarios previously mentioned (Bhattarai et al., 2022; Modi et al., 2022). Scenarios were reduced to minimize bias during simulation. HEC-RAS 1D solves Saint-Venant continuity and momentum equations (1D), considering key variables such as, river flow, depth flooding, Manning’s roughness coefficient, transversal sections, topography, land use, among others, which help to describe and evaluate flooding behavior under Climate Change (Edamo et al., 2023).

HEC-RAS 2D is used to analyze sea level rise (SLR), flooding changes in urban areas (Modi et al., 2022; Rahimi et al., 2020), and inundation mapping, under future periods and Climate Change impacts. It models under unstable flow, solving two-dimensional Saint-Venant equation, finite volume algorithm and diffusion wave equations (Roy et al., 2021), considering the same key variables as HEC-RAS 1D, but it includes bathymetry, high tide conditions, maximum river or sea flow and slope to obtain results related to direction changes and flooding extend in larger areas (Edamo et al., 2022; Rahimi et al., 2020). Coupled domain HEC-RAS consider effects of Climate Change under floodplain, riverbanks (2D), river channel (1D) and sensitivity under fluvial and coastal flooding (Chyon et al., 2023; Roy et al., 2021). Furthermore, it is used to evaluate flooding impacts by precipitation in urban areas, considering drainage systems (Das & Sahoo, 2025) and infrastructure built over the river (Sarchani & Tsanis, 2024).

Results obtained during flood simulation under Climate Change scenarios showed that some regions worldwide will witness increases flood extend, maximum precipitation and discharge (Bhattarai et al., 2022; Dysarz et al., 2024; Krylenko et al., 2025; Zhang et al., 2019; Mahato et al., 2022), volume and flood depth (Modi et al., 2022), influenced by flow changes, intensity and precipitations under RCM and RCP scenarios. Flooding changes increase proportionally with the return period (Mahato et al., 2022; Roy, et al., 2021), GEI emissions and land use changes (Modi et al., 2022; Pasquier et al., 2019). In coastal regions, sea level rise (SLR) increases, runoff (Krylenko et al., 2025) and precipitation changes (Rahimi et al., 2020; Zhang et al., 2019), which can be influenced by Tropical Cyclone (Zhang et al., 2019), will extend flooding areas and depths under winter seasons mainly (Krylenko et al., 2025).

MIKE-FLOOD is a hydrodynamic model highly used to assess several flood types under future Climate Change scenarios in urban and rural basins (Nguyen et al., 2021; Zewdie et al., 2024). MIKE-FLOOD consist of MIKE 11, which uses the 1D finite scheme to solve Saint Venant equations, using key variables such as, flow, water level, transversal sections, Manning's roughness coefficient, topography (Jahandideh Tehrani et al., 2021). Several investigations used it to assess Climate Change impacts on streamflow (Zewdie Werede et al., 2024), discharge changes (Anh et al., 2019) hydrologic and hydraulic responses (Horton et al., 2022; Jahandideh Tehrani et al., 2021) in fluvial and coastal flooding. MIKE 21 takes part of MIKEFLOOD but, it solves the two-dimensional Saint Venant numerical equations (Shrestha et al., 2020). MIE-21 uses the same key variables as MIKE 11, including land use, bathymetry and swirl viscosity (Anand et al., 2021). Researches carried out by authors as Paranunzio et al., (2022) and Tuan et al., (2024), demonstrate its efficiency to analyze future risk and SLR effects into costal dynamic. Meanwhile, Anand et al., (2021); Shrestha et al., (2020) and Triet et al., (2020) state its effectiveness to project dynamic floods influenced by Climate and land change, affecting hydrology, morphology and streamflow.

Authors used coupled MIKEFLOOD (1D-2D) to assess flooding risk under hydrological changes, influenced by Climate Change in future scenarios (Eccles et al., 2021; Jena et al., 2024; Le et al., 2021; Tuan et al., 2024). It facilitates flood analysis when exceeding cross sections heights under 1D modeling and represent floodplains (Gusain et al., 2020; Nguyen et al., 2024). Results revealed that fluvial and pluvial flooding will be influenced by reductions in high and medium flow rates, and increases in peak flood, flooding area and depth (Bhusal et al., 2025; Ho et al., 2023; Robi et al., 2019). Meanwhile in coastal flooding, streamflow is going to reduce significantly under RCP scenarios but, it will increase in smaller periods, influenced by SLR in zones such as Australia (Eccles et al., 2021).

Precipitation-Runoff-Flood (RRI) Model is used to evaluate Climate Change impacts on river flow, urban (Li et al., 2024), and modeling Mekong River Basin (MRB) and Cambodian floodplain under return periods (TR) considering scenarios and future periods. Results showed proportional increases with the flood magnitude and precipitation, as it increases (Triet et al., 2020; Try et al., 2020, 2023). It solves the diffusive wave equations under 1D-2D dimensions, using key variables such as, topography, precipitation, evapotranspiration, daily flow, transversal section, Manning's roughness coefficient, hydraulic conductivity (Li et al., 2024).

Authors have used SWMM model to assess Climate Change and urbanization impacts on volume, critical characteristics and risks on urban flooding (KC et al., 2021; X. Wang et al., 2024; Zhou et al., 2019). It uses key variables like, geometric characteristics, Manning's roughness coefficient, surface storage and soil infiltration model parameters. It is coupled with models such as, RRI and Newflood to assess fluvial and pluvial flooding and their changes under Climate Change scenarios. Hou et al., (2022) and Li et al., (2024) used it and identified flooding will be more frequent considering river investment, as well as, maximum volume, area, flood depth and overloaded wells increases under future periods.

CaMa-Flood model is used to investigate fluvial and pluvial flooding and floodplain changes under future Climate Change projections worldwide (Mohanty & Simonovic, 2021) and quantify risks, time changes and frequency of flooding, mainly in Canada (Gaur et al., 2018, 2019). CaMa-Flood solves the shallow water equations of diffusive open channel, within unit basins and local inertial flood equations. During modeling, it considers variables used by (Jahandideh Tehrani et al., 2021) and bench height. Results showed basins located in eastern and western cities will experience major changes in inundation extent, frequency under RCP 8.5 mainly. This can be influenced by winter precipitation and snowmelt.

Infoworks RS is a model used to identify and project future changes of urban coastal and pluvial flooding under Climate Change scenarios, which are associated with increases in SLR and rainfall (Kuok et al., 2022). It solves St. Venant equations for 1D flows pipes and channels, using variables selected by (Mohanty & Simonovic, 2021), including river networks, land use and precipitation. While, Infoworks ICM is a current model that simulates the behavior of rainfall flooding in sewer networks and watersheds, as well as, Climate Change impacts and land use changes, located in or adjacent to urban areas, (Liew et al., 2021) on flooding and extreme precipitation events under return period and GCM (Hosseinzadehtalaei et al., 2021). It solves the 2D shallow water equations, once the flood water overflows the riverbank, which moves in several directions.

Delft3D-FLOW model has been used by authors as, Iglesias et al., (2022), Lopes et al., (2022) and Melo et al., (2020) to identify future flooding and hydrodynamic characteristics changes, considering SLR, maximum fluvial flow and cyclonic storm surges in coastal and estuarine zones. It is coupled with models such as, TU-FLOW to incorporate the one-dimensional network function (Rahman et al., 2019; Shen et al., 2022). Delft3D-FLOW solves the Reynolds-averaged conservation equations for mass and momentum under secondary flow, considering key variables such as river flow, coastal water level, bathymetry, topography, rugosity coefficient, transversal section, among others (Iglesias et al., 2022). Results obtained during hydrodynamic simulation showed that estuarine area under longer return periods will be affected (Ganguli et al., 2020). In coastal zones, flooding areas and water level will increase proportionally to the return period (Kuok et al., 2022), which can be related to combined effects. On urban basin flooding area and volume depth will increase with the return period, as well as, maximum modeled flow rates (Liew et al., 2021).

Hydrodynamic model used for coastal flooding simulation on Climate Change impacts on SLR and Tropical Cyclones (TC) is ADCIRC, coupled with SWAN that solves the fluid motion, continuity and momentum equations under 2-3 dimensions. It employs key variables used by (Iglesias et al., 2022), including tide height (Marsooli et al., 2019; Marsooli & Lin, 2020). It was used in coastal areas of The United States to identify that Climate Change effects on TC under return periods greater than 100 years, will be significant at the end of the 21st century and increase with SLR in low latitudes. Similarly, FLO-2D model was applied to assess tropical cyclone-driven flood risks under Climate Change scenarios based on the same equations and key variables as ADCIRC (Zhang et al., 2019). It revealed under climate Change scenarios, Hadache River will experience severe flash flooding, influenced by significant increases in depth water and inundated area.

CoastFLOOD facilitates the identification of vulnerable coastal areas to Climate Change impacts, using the continuity equations and momentum equations, considering variables used by Iglesias et al., (2022). Skoulikaris et al., (2021) used it in their research and identified that Deltaic areas could change flooding probabilities and extend area, but extreme flood levels will be reduced by the end of the 21st century. TELEMAC is a model, which

solves the shallow water equations, considering key variables utilized by Iglesias et al., (2022). Researches made by Darlington et al., (2024), Gaeta et al., (2018) and Iglesias et al., (2022), highlight its efficiency when it is coupled with models such as Delft3D, MASCARET and JBA's 2D to flooding modeling under present and future Climate Change scenarios. COS-Flow is also efficient to model compound coastal floods changes under changing climates scenarios, demonstrating that wave heights, storm surge and inundation areas will increase significantly under future composite events (Hsiao et al., 2021). It solves the shallow water equations, which a term is added to the mass equation to accept the 1D modulo, taking into account key variables used by (Iglesias et al., 2022).

CH3D model was used by Peter Sheng et al., (2022) to analyze the sensitivity of composite coastal flooding under Climate Change scenarios based on averaged Navier-Stokes and Reynolds equations and considering the same variables as (Iglesias et al., 2022). ROMS model solves the primitive equations by finite difference methods and considers key variables selected by Jahandideh Tehrani et al., (2021). It is efficient to assess extend and duration flooding changes on coastal zones under Climate Change scenarios, which will be more intense and prolonged in the near future (Toste et al., 2024) Multiscale flood model (MSN-Flood) was used by Kirkpatrick et al., (2020) to assess urban coastal-fluvial flooding, considering Climate Change impacts and variables selected by (Iglesias et al., 2022). It is based on average SLR magnifications and solving the St. Venant equations to simulate speed, water elevations.

Other efficient model is Hydrodynamic-hydrological large-scale, which was used by Munar et al., (2023) and Petry et al., (2025) to evaluate and understand Climate Change impacts on fluvial discharges and flood extent in South America, considering hydrologic parameters, land use, topography and bathymetry. Tu et al., (2020) and Budhathoki et al., (2023) used CCHE2D and Rainfall-Runoff Coupling Flood Model (IMCR) to evaluate Climate Change impacts on extreme flows during the flooding watersheds, using key variables used by (Iglesias et al., 2022). It adopts the shallow water equations, which consider the depth water. Iber model is useful to assess Climate Change impacts on fluvial flood losses in urban areas, based on the finite volume method to solve two-dimension St. Venant equations. It considers key variables such as, maximum water level, land use, Manning's roughness coefficient, past flood extent, flow hydrographs, among others (Soriano et al., 2023). Under Climate change scenarios loss reduction and flood probabilities are expected in lower return periods, but it will increase proportionally in the future (Soriano et al., 2023).

GPU (HiPIMS) 2D model solves the shallow water equations and considers key variables such as, average speed, depth water, bed slope, input flow and Manning's roughness coefficient (Y. Wang et al., 2019). Due to its efficiency, Wang et al., (2019) used it to assess flood risk under Climate Change scenarios and hydraulic engineering. Two-dimensional Runoff Inundation Toolkit for Operational Needs (TRITON) was used by Dullo et al., (2021) to assess Climate Change impacts on flooding regimes, floodplain and existing infrastructure under past and future periods. It solves the nonlinear shallow water hyperbolic equations using an explicit volume upwind scheme and key variables selected by (Bhusal et al., 2025). Due to its efficiency, STREAM2D is used to evaluate flooding characteristics under Climate Change scenarios based on two-dimensional St. Venant equations in shallow water approximation, considering key variables obtained from ECOMAG and used by (Bhusal et al., 2025).

Under Climate Change scenarios, depth, peak flow (Dullo et al., 2021) maximum discharge (Krylenko, 2023) and floodplain speed will increase, as well as, frequency, which exacerbates the extent of fluvial flooding in the second half of the 21st century (Kirkpatrick et al., 2020; Munar et al., 2023), as return period increases in RCP4.5 and RCP8.5 (Krylenko, 2023). Nevertheless, the extend and depth flooding will not change drastically (Tu et al., 2020). During future 50-year floods with presence of hydraulic infrastructure, flooding will overflow the levee and reach significant areas and depths (Wang et al., 2019).

Results of the review demonstrate that worldwide flood hydrodynamic modeling under Climate Change scenarios and defined periods, has been relevant in areas with a risk history such as China, Canada, The United

States, Italy, Malaysia, India, among others, to obtain an overview of changes in present and future events. This is the basis to consolidate strategies for prevention, control and timely management of the risk associated with their occurrence. Nevertheless, there are areas around the world that, despite having a history of major impacts on flooding behaviors due to Climate Change, no researches have been conducted to reveal their current and future conditions, therefore, their risks and impacts could become catastrophic if the knowledge base is not available to take timely actions.

A large number of hydrodynamic models have been used under Climate Change scenarios, which have been selected considering the current situation, type of flooding, data availability and objective projections. One of the most widely used models are HEC-RAS and MIKEFLOOD, due to its capacity and efficiency to model fluvial, pluvial and coastal flood in one and two dimensions and display accurate results, which show how Climate Change will generate changes in the near future. HEC-RAS, being a free license model, allows it to be used in several investigations and by authors to model water flows and analyze their behavior under approximate scenarios, while MIKEFLOOD use seems limited for being a licensed software and requires financial support (**Table 1**). There are other hydrodynamic models, such as Delft3D, SWMM, CCHE2D, Rainfall-Runoff Coupling Flood Model (IMCR), among others, which have efficiency and accuracy to model flooding under Climate Change scenarios, but these are not widely used and recognized. Therefore, through this review, their capabilities are highlighted, so they can be used in areas with similar background and characteristics.

According to several authors, the Climate Change scenarios at the global and regional scale created by the IPCC, considering greenhouse (GEI) emissions, atmosphere changes, ocean and mean temperature, under different periods, have degrees of uncertainty in the available data, therefore, it could not reflect the real situation and raises concerns about the results obtained throughout the modeling. For this reason, it is recommended they must be corrected prior to modeling to reduce the biases and ensure accurate results are obtained. It is important to consider these scenarios are approximations that could change significantly under extreme events occurrence. Nevertheless, they are currently the only existing knowledge base for projecting possible future flood changes under Climate Change scenarios, to manage risk and potential impacts prior to their occurrence or subsequent mitigation.

Conclusions

The analysis and retrieval of scientific production carried out within the implementation of hydrodynamic models facilitated the selection of highly relevant research. Several models are used to simulate flood under future Climate Change scenarios defined by the IPCC. Though, during its selection, the current situation, flooding type, data availability and projection objectives must be considered. In such way, the results obtained are valuable and consistent for decision making.

The most widely used models worldwide are HEC-RAS and MIKEFLOOD, due to its capacity and efficiency to model various type of flooding and display accurate results. There are other hydrodynamic models, which have efficiency and accuracy to model flooding, so they can be used in areas with similar background and characteristics.

The review reveals use of hydrodynamic model in research, conducted in areas with a history of occurrence. Nevertheless, the development of investigations in areas of interest is required to deal with future events in a timely manner and reduce potential impacts.

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Author 1: review, writing (lead) and formal analysis Author 2: Conceptualization (lead) and review Author 3: Conceptualization (supporting) review and editing.

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Table 1. Main benefits and difficulties of the most commonly used flooding models

Hydrodynamic model	Benefits	Difficulties
HEC-RAS	Free model to model floods and obtain results under different visual elements (Pasquier et al., 2019). Pluvial, fluvial and coastal flooding modeling under Climate Change scenarios, in 1D(river)-2D(river-floodplain) for artificial and natural channels (Roy et al., 2021) Advantages for simulating overbank flooding and the presence of hydraulic infrastructure (Modi et al., 2022)	Results and predictions depend on quality of input data required to simulate (Roy et al., 2021).
MIKE-FLOOD	Flooding dynamics modeling under 1D-2D dimensions in the riverine, floodplain, urban zones and channel system (Anand et al., 2021). It considers key variables such as, wind speed, eddy viscosity, wave radiation, which helps to obtain more realistic results (Sherestha, 2020).	Licensed software, which limits its use under flood modeling. Under one dimension it is not provide detailed information about extensive flood (Sherestha, 2020).
Delft-3D	Open software to simulate and estimate the hydrodynamics and flooding changes on estuarine, fluvial and coastal zones under multi-dimensions and Climate Change impacts (Rahman et al., 2019).	Simulation fate depends on initial conditions adjustment to ensure modeling stability and obtain accuracy results (Ribeiro et al., 2021)
SWMM	Coupled with models to capture more detailed comprehension about flood characteristics	This cannot simulate surface flooding conditions, what requires the use of

	promoted by Climate Change, under future periods and resolutions (Hou et al., 2022).	indicators that summarize them (Zhou et al., 2019).
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