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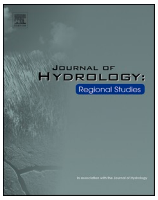

Review of flood modelling and models in developing cities and informal settlements: A case of Nairobi city

Randa O. Tom[a,c,*], Krhoda O. George[b], Atela O. Joanes[a,c], Akala Haron[a]

[a] African Centre for Technology Studies, Kenya
[b] The Department of Geography, University of Nairobi, Kenya
[c] The Africa Research and Impact Network, Kenya

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ABSTRACT

Study region: This study focuses on urban flood modeling in developing cities with a special focus on informal settlements giving a specific case study of Mukuru slums in Nairobi city of Kenya. Informal settlements refer to unplanned settlements and areas where the housing doesn't comply with the current housing codes and regulations and is thus characterized by a lack of legal settlement and housing plan approvals resulting in poor physical infrastructures and social services. Urban flood risks have been given less attention compared to rural riverine flooding in developing cities yet they cause more havoc. Using the appropriate set of models, flood modeling in urban settings is critical in integrated flood risk management.

Study focus: This study uses a desk review format to promote urban flood modeling knowledge and practice in integrated flood risk management in developing cities. In this regard, the study presents the review of various flood models highlighting their strengths and weaknesses and the significant role of model calibrations in addressing uncertainties while capturing the local scenarios. The paper further presents the role of model stacking where different models are used to understand the same hazard evolution at various scales.

New hydrological insights for the region: As developing cities grow, so do the flood risks, especially in the informal settlement. This study reveals the importance of comprehensively understanding the flood dynamics at various scales. The study points out the important role of model stacking and calibrations which allows the understanding of flood risks at various city scales for an integrated city flood risk management.

1. Introduction

While flooding is experienced in rural and urban settings, its occurrence in the urban setup has a unique nature as the built environment and the growing population plays a significant role in its occurrence besides the predominant causal factor of natural variation in rainfall intensities and durations. The effects and the subsequent impacts of flooding are much felt in populated areas such as the urban setups with the worst cases of negative impacts felt in the informal settlements (Nassar and Elsayed, 2018). Informal settlements refer to unplanned settlements and areas where the housing doesn't comply with the current housing codes and regulations and is thus characterized by a lack of legal settlement and housing plan approvals resulting in poor physical infrastructures and social

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* Correspondence to: P.O. Box 45917 – 00100, Nairobi, Kenya.
E-mail address: tomranda12@gmail.com (R.O. Tom).

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services. These characteristics associated with informal settlements, most common in developing cities, make them highly vulnerable to flood risks (Dawson et al., 2008). Over the years, urban flooding has been experienced in cities with devastating impacts in the informal settlements of developing cities and more are to be expected with the rapidly growing informal settlements coupled with climate change impacts. In as much as efforts are continually being made to make cities more resilient, more is yet to be done to achieve the much-desired goal of sustainable and reliant cities, especially in developing countries. Urban flooding is commonly experienced in developing cities leading to the destruction of properties and disruption of services; loss of livelihoods and economic disruptions; destruction of critical infrastructures, and loss of lives. These adverse impacts of urban flooding are more pronounced among the urban poor, who mostly reside in the informal settlements of developing cities. The trend is a concern for developing cities due to the limitations in research, economy, and policy frameworks and therefore warrants such studies to explore the potential of flood modeling at various levels of the city in an attempt to address the current and potential flood risks in the city and reduce the impacts among the urban poor (Neal et al., 2012).

As cities grow both in urbanization and population, so does the risk exposure with the sprouting and expansion of informal settlements. More than two-thirds of the global population is expected to live in urban settings by 2050 with a majority of this urban growth expected in developing cities (United Nations et al., 2019). In as much as the high rate of urbanization and population growth in the developing cities could be a sign of economic growth and progressive urbanization, it is also a signal of the high exposure to hazard risks and vulnerabilities to disasters following the low adaptive capacities associated with these cities manifested in the sprouting and growth of the informal settlements. Coupled with the projected unpredictable rainfall and severe climatic conditions under climate change, urban floods are expected to increase in their frequencies and intensities with devastating impacts in the informal settlements if proactive measures are not put in place (Teng et al., 2017a). Recent studies conducted in Narok town revealed that land use and land cover changes directly impact the flood intensities and frequencies in developing cities. The increased land use and land cover changes associated with urbanization are thus major contributors to the increasing flood peaks in developing cities (Umukiza et al., 2021). This calls for the adoption of effective integrated flood risk management approaches to effectively address the flood hazard risks at both levels (Beven and Binley, 1992). Such effective flood risk management practices include planned and controlled integrated land use in cities, soil conservation measures, agroforestry practices, drainage maintenance, and sustainable city planning and development. As such, the best practices of integrated flood management are supported by flood risk modeling, to ascertain the previous history of flood hazards, understand the current flood risk and predict future possible flood risks under different scenarios (Bates et al., 2005a).

In as much as this study takes the form of a systematic literature review to explore the various urban flood models applicable in developing cities, the study presents the case of Nairobi city and showcases the significant role of model calibration and model stacking in understanding the flood dynamics at the city and sub-city level (informal settlements) and thus effectively informing flood risk management at both levels. In this study, model stacking refers to the process of combining the outputs of multiple model algorithms to enhance the prediction of the model to best capture the local contexts and processes (Pedersen, 2022). The main concept of model stacking, where one model outputs are used in the next high precision model to optimize the simulation and prediction of the local phenomenon at the local contexts and process, was highly emphasized. In this regard, this review focuses on some widely used flood models that exist in the current literature and evaluates their capability and suitability to simulate flood hydrodynamics in developing cities. The review is timely since advances in flood modeling have evolved rapidly in recent years to be a critical component of flood risk management that need downscaling to the informal settlements to address the current and potential flood risks and the eminent adverse impacts that are more pronounced among the urban poor. More specifically, the review is done under the broader Tomorrow's Cities Project, funded by the UK Research and Innovation Collective Fund award to reduce risks from multiple hazards and hence build resilience among the urban poor. The study is thus critical because it goes beyond the review of various flood models to showcase the role of model calibration and model stacking application in urban flood modeling to adequately address the city-wide and sub-city level flood risks using the case of Nairobi.

2. Methodology

The study was conducted using a desk review to achieve the study objectives. Relevant literature was searched, reviewed, and synthesized in this study (Pillai, 2020). The keywords for the literature search were defined to allow optimal literature search from the different databases and Journals. The keywords included *Urban Flooding, Flood modeling, Uncertainty estimation, hydrodynamic models, flood risk management, model calibration, and stacking*. The literature was searched and retrieved from different databases primarily through google scholar. The various journal articles were retrieved mostly from Science Direct (www. sciencedirect.com) and the Elsevier Journals information portal. The literature was limited to those from 1990 onwards to ensure the review of the most recent literature and modeling techniques. The gathered literature was integrated with the other literature and information sources such as reports, briefs, and books known to the author before the review (Snyder, 2019). The systematic review focuses on the flood models exploring their application strengths and limitations, how they address the uncertainty issues, and the current and future development directions in urban flood modeling and management. In this regard, the study is organized into four sections. The first part presents the introduction outlining the background of urban flood modeling, stating the key objectives and justification of the review. The second part discusses the methodology used pointing out the limitations of the applied literature review method and the outline of the paper. The third section gives the findings thematically grouped to capture the different flood types common in urban areas, explore various flood models 'strengths, and the significance of model calibration capturing both uncertainty and sensitivity analysis before presenting the state of flood modeling in Nairobi as a case study and highlighting the importance of model stacking in flood modeling. The study concludes with the fourth section capturing general conclusions and providing an overview of the study findings and flood modeling applications.

3. Findings

3.1. Urban flood types and risks in developing cities

Stormwater normally has its natural pathways as they flow through gravity in a specific manner. Urban floods occur when the storm waters overwhelm the existing drainage systems and are enhanced when the drainage systems are blocked or waterways are diverted (Okoth et al., 2016). Anthropogenic processes in urban areas such as land use and land cover changes interfere with the natural stormwater flow and artificial waterways are normally developed to replace or adjust the natural water flows. These occur due to the growing urban populations and the competing development needs that tend to alter the land surface and hence the water flows. In some cases, unplanned and uncontrolled settlements associated with informal settlements in developing cities allow settlement on the flood plains and the waterways thereby increasing the exposure to flooding risks. Fig. 1.

Fluvial floods normally occur when the streams overflow due to a prolonged rainfall of high intensity, ice melt, or sea-level rise. In developing cities such as Nairobi, fluvial floods are less common but cannot be ruled out since several riverine tributaries meander through the city downstream. Fluvial flooding usually affects a wide area mostly downstream of a river which tends to be relatively flat and associated with several meanders. Pluvial flooding, the basis of this paper, is most common in cities as it is caused by an intense rainfall storm independent of the overflowing of the rivers and streams. The developing cities and mostly the informal settlement are the major hotspots of pluvial flooding which pose a threat to the fundamental steps to the achievement of sustainable development goals (Zscheischler et al., 2018).

In as much as the increased intensities and frequencies of rainfall is the major causal factor of pluvial floods, other causes have been identified in recent past studies. Dawson et al. (2008) identify land-use change, overwhelmed and in some cases unmaintained urban drainage system, and poor urban planning as the causal factors of urban pluvial flooding. Mark et al., 2018 explain pluvial flooding in terms of the scale of its impacts which positively correlates to the large human population and developed assets in the urban settings (Mark et al., 2018; Carter and Parker, 2009).

The risks and the impending threats from the urban floods in developing cities are real and worrying due to several reasons. First, studies focusing on flood risk management show that a few flood hazard modeling studies exist for informal settlements in Africa. This implies less evidence to support targeted integrated flood risk management in the informal settlements. This has led to inadequate informal settlement targeted and evidence-based flood risk management measures and policies in most developing cities in cases where they do exist. Secondly, the hydrodynamics of the urban floodwaters undergo a series of interference due to the complex nature of the urban setups and thus pose a significant challenge to parameterizing most of the factors for studies (Mignot et al., 2006). The increasing impervious surfaces of the urban centers reduce the rate of infiltration while increasing the development of surface runoff causing more havoc during floods. Thirdly, various anthropogenic activities such as settling on flood plains and waterways, clogging of drainage in the cities, diverting of streams, and reducing infiltration due to uncontrolled and unplanned constructions enhance the

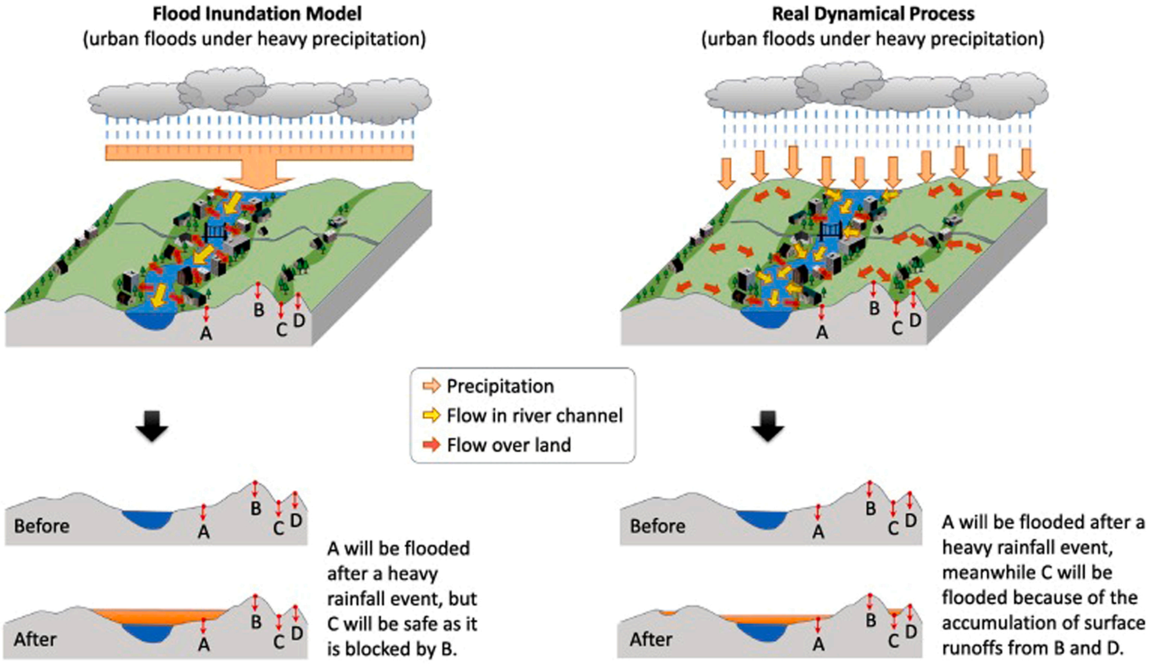

Fig. 1. Schematic representation of rainfall–runoff/flooding processes in urban areas.

threats of urban pluvial floods. Fourthly, the rapid population growth and high urbanization rates supersede the supply of housing, sanitation, and other critical infrastructural facilities and services in developing cities leading to the proliferation of informal settlements which enhances the vulnerabilities of the urban dwellers to various disaster risks including flood risks (Braun and Aßheuer, 2011). Finally, the little knowledge of the flood risks, impacts, and threats in these areas enhance the risk itself as it makes the city more vulnerable and unprepared and thus unable to alleviate the negative impacts of urban flood risks.

3.2. Flood models classifications

Since the study involves reviewing various deterministic flood models that have been used in urban flood studies for different purposes, including flood forecasting, flood hazard mapping, simulations, and flood risk estimation. In this regard, the broader categories of flood models in urban flood studies include empirical, hydrodynamic, and conceptual models.

3.2.1. Empirical models

The empirical models also known as the black box models contain parameters that may have physical characteristics that allow the modeling of input-output patterns based on empiricism (Jun et al., 2016). The empirical flood models rely heavily on historical data gathered, integrated, processed, and analyzed and are thus considered accurate and a representation of the observed realities. The modeling is considered robust and accurate based on the reflection of the observed realities in the past used as inputs into the model. In as much as the modeling technique based on empirical models has gained much research attention, continual development and improvement are necessary. The outputs of these models are widely used to support decision-making and serve as inputs to other methods (Hlavcova et al., 2005).

3.2.2. Hydrodynamic models

Hydrodynamic Models are those based on fluid dynamics where the computations of waves and fluids motion are the basis of simulation. The models simulate water movement by solving fluid equations based on physical laws. Depending on the spatial dimension representation of the fluid flow, the hydrodynamic models can be classified as - dimensional, two-dimensional, and three-dimensional flood models (Bates et al., 2005b).

3.2.2.1. dimensional models. One-dimensional flood models represent the channel and floodplain as a series of cross-sections perpendicular to the flow direction and solve the one-dimensional Shallow Water Equations (Bates and Roo, 2000). Several hydraulic situations may apply the one-dimensional hydrodynamic modeling when the solution doesn't require knowledge of the other dimensions. They are the simplest of all hydrodynamic models, computationally efficient since the flow is assumed to be in one direction, steady and at a homogenous velocity across the flow channels (Bates and Roo, 2000). The application of 1D flood models in urban areas may overlook the significant hydrological and hydraulic characteristics that define urban floods needed to be parameterized in model simulations and predictions for effective decision making. (Horritt and Bates, 2002). Dimension flood models are derived by solving mass and momentum conservation equations between two cross-sections Δx apart yielding the famous one-dimensional Saint-Venant equations:

$$\text{Conservation of Mass}\quad \frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=0\ldots\ldots\ldots \tag{1}$$

$$\text{Conservation of Momentum}\quad \frac{1}{A}\quad\frac{\partial Q}{\partial t}+\frac{1}{A}\quad\frac{\partial\left(\frac{Q^2}{A}\right)}{\partial x}+g\frac{\partial h}{\partial x}-g\left(S_0-S_f\right)=0\ldots\ldots \tag{2}$$

Where Q is the flow discharge, A is the flow cross-section area, t is the time, h represents water depth, is the gravitational acceleration, S_f is the friction slope and so is the channel bed slope.

While the one-dimensional hydrodynamic model has the merit of low input data requirements, they have the broader limitations of misrepresenting critical hydrological processes (Ali et al., 2015). Several efforts are continually being made to enhance the performance of these models especially in simulating urban floods and thus one-dimensional models may not adequately simulate urban floods in developing cities where the micro features play a central role in riverine and flash floods. For instance, Mark et al. (2004) study of urban floods using a one-dimensional model reveals that while flood modeling is possible using the one-dimensional models, there exist uncertainties in the model outputs due to the treatment of topography data and urban flow characteristics as one dimension.

3.2.2.2. Two- dimensional models. Generally, the 2-D models represent the floodplain flow by considering two-dimension fields assuming the third field which is usually water depth is shallow and thus assumed in solving the two-dimension shallow water equations (Nkwunonwo et al., 2020). The two-dimensional flood models such as TUTFLOW and MIKE 21 solve the two-dimensional SWEs using appropriate numerical schemes. In other words, the models solve the 2D shallow water equation, which is a representation of mass and momentum conservation in a plane mode and depth-averaging of the Navier- Stokes's equation:

$$Conservation\quad of\quad Mass\frac{\partial h}{\partial t}+\frac{\partial(hu)}{\partial x}+\frac{\partial(hv)}{\partial y}=0\ldots\ldots\ldots\ldots\ldots\ldots \tag{3}$$

$$\mathit{Conservation\quad of\quad Momentum}\frac{\partial(hu)}{\partial t}+\frac{\partial}{\partial x}\left(hu^2+\frac{1}{2}gh^2\right)+\frac{\partial(huv)}{\partial y}=0\ldots\ldots \tag{4}$$

$$\frac{\partial(hv)}{\partial t}+\frac{\partial(huv)}{\partial x}+\frac{\partial}{\partial y}\left(hv^2+\frac{1}{2}gh^2\right)=0\ldots\ldots\ldots\ldots\ldots \tag{5}$$

Where x and y represent the two spatial dimensions and the (u,v) are 2D vectors representing the horizontal average velocity of the flow.

The solution of these equations gives estimates of horizontal velocity and depth of the flow. It is evident that 2D hydrodynamic models are the most widely used in flood mapping and assessment studies and thus widely documented. Several scholars have also reviewed the capability of 2D models in flood modeling. For example, (Hunter et al., 2008) comprehensively review the performance of several 2D models in capturing urban flood hydrodynamics. Neelz and Pender (2010) further reviewed by benchmarking of 2Ddraulic Modelling Packages and found out that while the urban areas present more localized simulation challenges in flood modeling, the 2D models significantly capture dynamics of flows and are thus effective in flood modeling studies (Hunter et al., 2008). A major advantage of the two-dimensional flood models is the comprehensive representation of flow hydrodynamics along with small-scale topographic features which seem to have significant contributions to urban flooding. Two-dimensional flood models are increasingly being applied in the prediction of the flood of all sources and so account for the optimal performance achieved in flood modeling, although the lack of rigorous model calibration still constrains the application of these models in developing cities (Xing et al., 2019).

3.2.2.3. Three-dimensional models. In as much as it seems complex and at times unnecessary since the 2D representation may be adequate to simulate and predict flow dynamics of various scales, the 3D modeling allows modeling of vortices, vertical turbulence, and multiple spirals flow at various bends and thus critical in understanding catastrophic flooding emanating from dam outbreaks, flash floods, tsunamis among others. Overall, the 2D hydrodynamic models were developed to capture vertical features of flows. While some 3D models solve the horizontal flow with 2D SWE and include a quasi- 3D extension to model velocity in vertical layers, others are derived from the 3D Navier- Stokes equations describing fluid flow and are normally written as:

$$\mathit{Conservation\quad of\quad momentum}\frac{\partial u}{\partial t}+u.\nabla u+\frac{1}{\rho}\nabla p=g+\mu\nabla.\nabla u\ldots\ldots\ldots\ldots\ldots\ldots \tag{6}$$

$$\mathit{Incompressibility\quad condition}\nabla.u=0\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{7}$$

Where u is the flow velocity, ρ is the fluid density, p is the fluid pressure, g is the gravitational acceleration and μ is the kinematic viscosity. Eq. (6) is based on the application of Newton's equation $F=ma$ to fluid motion and Eq. (7) is based on the fact that the fluid density is constant within a fluid parcel (Teng et al., 2017b). Depending on the nature of the representation of the process, the models can further be classified into Eulerian (grid-based) or Lagrangian (Particle-based).

The uses of 3D flood models had been considered not viable for flood inundation reaching above one kilometer due to lack of computational capabilities, inaccuracy in representing free surface flows, and high order turbulence (Cleary et al., 2007). However, this limitation has eased in the recent past following the development of high computing techniques and the development of particle-based modeling techniques. The particle-based modeling techniques allow the representation of micro-scale features and units smaller than grid cells, thus eliminating spatial diffusion need problems for spatial discretion (Cleary and Prakash, 2004). Nevertheless, the use of 3D modeling in flood inundation is recent, and thus limited literature is currently available compared to 2D flood inundation modeling.

3.2.3. Simplified conceptual models

These are models that don't simulate the physical processes associated with fluid flow and inundation but are majorly concentrated in simplified hydraulic concepts. As much as they may fit within the two-dimensional classification due to their dimensional representation of flows, they are not hydrodynamic models. These models solve the simplified shallow water equation by omitting one or two acceleration terms (Neelz, and Pender, 2013). A good example of the non-physics-based models is the Rapid Flood Spreading Method which works by basically segmenting the flood plain according to topographic depressions and then spreading the flood volume by filling these depressions progressively according to the elevation and size (Lhomme et al., 2008). This conceptual methodology also forms the basis of the Flood Modeler Pro 2D fast solver. These models can be used to predict final inundation within a short time since they require less computational capacity need compared to hydrodynamic models (Hlavcova et al., 2005; Mark et al., 2004).

Other sets of conceptual models are based on the theory of the “planar method” where the flood extent is derived by the model intersecting several fine resolution plains using high-resolution Digital Elevation Models and directly linking water volumes with flood extents (Teng et al., 2015). Other models such as the Height Above the Nearest Drainage (HAND)model work by normalizing the topography of the area of interest relative to the local heights of the nearby stream and estimating the flood inundation by selecting the cells whose model simulation values are less than the known long term water depth in the nearby stream (Nobre et al., 2011). More generally, conceptual models require less intense computational demands and are thus useful tools in large-scale applications where the flood extents and depths are the only required outputs as dynamic effects are assumed to be insignificant.

3.3. Strengths and limitations of flood models

Different modeling techniques have their advantages and limitations. Specific models also have their strengths and limitation. In this paper, the strengths and limitations of models are analyzed in two stages to capture the general classification or categories as well as the specific models.

3.3.1. Analysis by models classification

The overall strengths and limitations of the broader modeling categories and their suitability for the various flood studies are summarized in Table 1 and discussed below.

3.3.1.1. Empirical models. These models are perhaps the most instinctive and straightforward tools to understand flooding characteristics based on records and related input data. They are normally assumed to be accurate since flood events have a certain history cycle of occurrence. However, the accuracy is highly dependent on the acquisition and processing methods adopted for the flood modeling, and therefore high accuracy demand more costly acquisition processes and complex processing techniques for the input data. The models are largely dependent on the wisdom of hindsight since they are a snapshot of the past and are thus limited in capturing the possible response to possible future scenarios or changes. The limitation of the spatial and temporal coarseness of resolution of the outputs was common but these are improving with the use of remote sensing in data gathering.

Other possible limitations of the methods and models include engineering faults associated with sensor design, operations, and transmission, environmental drawbacks such as adverse weather conditions and other natural factors, and the accuracy of the algorithms in data mining and processing imply the output information. Since these models are purely adopting the input-output approach based on records, any artificial error in the entire chain of processes can jeopardize the credibility of the resulting outputs and the decision-making information being shared.

3.3.1.2. Hydrodynamic models. These models are widely used tools in detailed flood dynamics simulations and are mostly linked to flood forecasting, mapping, and scenario analysis both in research and operations. The critical characteristics of hydrodynamic models that perhaps explain their widespread usage in various applications are the ability to manipulate their inputs to investigate the impacts of changes in the initial conditions, boundary conditions, and topographic changes arising from the change in critical hydrodynamic features such as river streams, culverts, and stream channel volume. The 1D hydrodynamics are usually computationally efficient since they consider flows in one direction and assume their steady and uniform. However, they have several limitations which include the inability to capture lateral and vertical wave diffusions of the flood waves, considering topography as cross-sections rather than the continuous surface, and thus somehow subjective in factoring in orientation and topographical cross-sections (Horritt and Bates, 2002). The 2D hydrodynamics generally can accurately simulate inundation timings and durations and are thus commonly used in

Table 1
Comparative summary of strengths and limitations of various models based on their classifications.

Model Classification	Strength	Limitation	Application Suitability
Empirical	coarse	• coarse spatial and temporal resolutions • Doesn't consider the hydrology and hydrodynamics thus not suitable for scenario modeling • Rely on hindsight wisdom derived from archived/observed data • Errors can easily cascade from the input data to the outputs. • Engineering limitations such as sensor defaults, transmission errors, and processing can easily be propagated in the model inputs.	Suitable for flood damage/impact assessment and flood monitoring
Hydrodynamic	• Captures the hydrology of the area (Allows simulation of hydrological system of the area of interest), • And Captures hydrodynamics and hydraulics features • Accurate inundation estimations in terms of timing and duration besides the quantity and depths.	• Computationally intensive due to the hydrodynamics and hydraulic considerations capturing physical laws. • Requires high data inputs • Input data errors can propagate in time and multiply in the processing chain.	Multiple applications such as flood risk assessment, damage/impact assessment, water resource planning, river system hydrology, and scenario modeling sediment transport studies, flood plain ecology among others.
Simplified Conceptual	• Simple and easy to use, • Less computationally intensive	• Inertia term is assumed in solving the shallow water equations, • Representation of flow dynamics is limited.	Applicable for flood risk assessment, water resource planning, scenario modeling, river system, and catchment hydrology.

Table 2
Summary of the Hydrodynamic Models highlighting their strengths and Limitations.

s/no.	Model Name	Developer	Dimension	Strength	Limitation	Access/ Status	Notes
1	TUFLOW 1D	BMT- WBM (1990)	1-D	Computationally fast, ability to link various domain dynamics.	Poor simulation of processes, and uncertainties in the solutions.	Commercial	Solves the full one-dimension shallow water equation
2	ISIS-1D	CH2M HILL (2008)	1D Hydraulic	Applicable and suitable for steady, unsteady, and transition flows	Unsuitable for flood dynamic simulations as it assumes constant velocity of flows.	Commercial	Suitable for simulating flows and levels in open water channels.
3	HEC-RAS 1D	Army Corps of Engineers (1995)	1D Hydraulic	Widely documented, wider applicability since it's easy to set, highly adaptable to various applications, and data quality.	Unstable and limited to the one-dimensional modeling environment.	Free to access	Solves the 1D energy equation for steady flows.
4	Newer MIKE 11	DHI (1997)	1D Hydraulic	Supplemented by numerous extensions and accompanying modules for river modeling	Suitable and thus limited to fluvial flooding events, unstable in 2D environment conditions	Commercial	Simulates river flows, levels, water quality, and sediment transportation.
5	ISIS 2D	CH2M HILL (2009)	2D	Suits a wide range of applications including hydrodynamic flood simulations	Requires high-resolution terrain data input and very slow simulation speed.	Commercial	Solves the full 2D shallow water equation. Can either work as a stand-alone or within the ISIS suite.
6	TUFLOW 2D	BMT-WBM (1997)	2D	Satisfactory representation of physical processes, Capability to link dynamic processes from various domains.	Relatively slow in simulation	Commercial	Simulates complex flow dynamics by solving the full 2D shallow water equation
7	MIKE 21	DHI	2D	Capable of simulating flow characteristics (velocity and direction), Applicable in flood dynamic simulations.	Simulations time steps must be manually calibrated, to ensure model stability, more calibrations needed	Commercial	Solves the full 2D SWE.
8	TRENT	Nottingham University	2D	Ability to capture the different flow and hydrodynamic shocks	Relatively stable when calibrated using adaptive stepping.	Commercial	Relatively good in capturing the hydrodynamic properties by solving the 2D shallow-water equation.
9	TELEMAC	Électricité de France (EDF) 2010	2D	Can simulate permanent and transient hydrodynamic conditions	Stable under specific conditions	Free to access	Designed to reduce the representation of process limitations in flood plains and stream simulations.
10	SOBEK	Deltares	2D	Ability to capture wetness, dryness processes, wind, and surface frictions on spatially varying surfaces.	Subjected to conditional stability	Commercial	Highly suitable by design for overland flows
11	DIVAS	Cardiff University	2D	Generally stable unconditionally and operate constant time steps	Inability to capture simulation shocks	Commercial	Solves the full 2D shallow water equations
12	CADDIES	Ghimire et al. 2013 (Ghimire et al., 2012)	2D	Relatively fast in simulating flooding and suitable for urban areas	Lacks intensive validation	Free to access	Use the Cellular Automata approach in flood simulation
13	Flo-2D	Jimmy S O'Brien (O'Brien and Zhao, 2012)	2D	Ability to capture both hydrologic and hydraulic processes and features. Applicable in both urban and river flood modeling	Computation of hydraulic features such as bridges and culverts must be done externally using specified methods and models.	Commercial	Solves the full 1D and 2D shallow water equation
14	LISFLOOD	(Knijff et al., 2010) (Roo et al., 2000)	GIS-based	Wide range of applications. Captures rainfall interception processes e.g., evaporation, an	Cannot operate as a stand-alone and requires a base platform.	Research	Is a Rainfall-Runoff-Routing Model

(*continued on next page*)

Table 2 (*continued*)

s/no.	Model Name	Developer	Dimension	Strength	Limitation	Access/ Status	Notes
				interception by vegetation, etc.			
15	MIKE URBAN 2010	DHI Water and Environment	Coupled 1Dand 2D	Integrated GIS capabilities, Applicable in simulating Urban flows	Inability to capture some hydrodynamics such as shocks and supercritical flows during simulation	Commercial	Works within the mathematical framework of 1D unsteady flow
16	HEC-RAS 2D	Army Corps of Engineers	2D	Wide references, Wide range of applicability, deploys several schematization complexities.	Inability to perform water quality modeling in 2D flow areas.	Free to access	Solves both the 2D St Venant equations and the 2D diffusion wave equations through an implicit finite-volume solution.

different applications. However, they are computationally intensive especially when covering a large study area since they solve the full shallow-water equation (Neelz and Pender, 2010). The 3D hydrodynamic models are generally considered not viable when covering an area of more than 1000 square Kilometers especially when a high-resolution simulation is required. They are computationally intensive and may take prohibitively long and thus not reliable for quick forecasts that give enough lead time for interventions (Beven and Binley, 1992).

3.3.1.3. Simplified conceptual models. These models require less computational capability than the hydrodynamic models. They are relatively fast and robust and are most suited for applications that don't require flow velocity outputs and low demands in flow dynamics accuracy and representations (Teng et al., 2017c). The less computational requirement implies that conceptual models have a high runtime saving and are thus suitable for a large flood plain simulation and probabilistic risk assessment that demands multiple and large number simulations. The models simulate flood extents, water depths, and overbank volumes much well on flood plains with clear flow paths but get more complicated in areas with complex topographies where momentum conservation is a significant factor. Overall, conceptual models have no representation of flow dynamics or force fields, don't capture wave dynamics, and thus don't predict flow velocities (Lhomme et al., 2008). The application of conceptual models is thus limited to areas of application where the flow dynamics effects are less significant in determining the direction and inundation characteristics. Table 2.

Overall, the study reveals that most flood models can be applied in urban flood studies irrespective of their classification. However, each and specific model has its strengths and weaknesses that must be considered in every study and application as their objectives vary. The strengths of hydrodynamic models allow their application in informal settlements where the land-use changes are dynamic and the complexities of socio-economic factors come to play (Wamuchiru, 2012). The resolutions of the data inputs, and the driving hydrological and hydrodynamics equations also determined the extent of the localized flood modeling in informal settlements. To best address flood hazard risks in informal settlements, the application of hydrological models that not only captures the rainfall runs off phenomenon but also allow the simulation and prediction of the flood movements and spread, the existing and potential hydraulic systems and allows possible scenarios development based on the land use and land cover changes among other socio-economic inputs. One of the major challenges of flood hazard modeling and forecasting in informal settlements is the availability of reliable high-resolution input data that need to be addressed in various developing cities (Neal et al., 2012). However, there exist various gridded reliable data sets that are continually bridging the gap. Moreover, the flooding in most informal settlements usually manifests as part of a sub-catchment, whose characteristics provide some clue on the hydro-climatic patterns in the area of interest. Since models are as good as the input data and the driving equations with their limitations, the review calls for a proper choice of flood model for informal settlement flood studies and encourages their localization through calibration and validation processes using local ground truth data for valid and reliable outputs.

3.4. *The role of model calibration in flood modelling*

All flood models have their strengths and limitations regardless of their dimensionality, complexity, and mathematical frameworks. In this regard, it is nearly impossible to have a perfect model to solely simulate the natural hydrodynamic processes and thus flooding in urban areas (Teng et al., 2017b). These complexities of simulating urban floods become more evident in developing cities where the microenvironment land physical processes contribute significantly to the urban flood dynamics and thus need to be well-captured in the model simulations (de Oliveira et al., 2019). Flood modeling, however, remains the core and perhaps the future of effective integrated flood risk management, and thus the focus is on how best to use and improve the flood models and modeling processes especially in developing cities where the impacts of floods are most pronounced (Reynolds et al., 2020). This study reveals that the calibration of the existing state-of-the-art flood models allows contextualization and parameterization using the local and context-specific input datasets and thus allows flood modeling in developing cities (Bout and Jetten, 2018).

Model calibration is therefore a significant process that allows the application of the existing flood models in developing cities. However, the discussions around model calibration always point to the concepts of uncertainties that must be determined and incorporated into the modeling process to ensure the results are sensible enough for the area of study (Dottori et al., 2013).

Uncertainties in flood modeling may arise from the input data, methodology or even the theory underpinning the specific modeling framework and these may undermine the accuracy and reliability of the research and flood risk management efforts (O'Brien and Zhao, 2012), (Knijff et al., 2010). Uncertainties in flood models may contribute to the under or over-estimation of the flood phenomenon and characteristics making the outputs unrealistic and thus misinforming the subsequent decisions (Koks et al., 2015). Flood model calibration, therefore, tends to play a critical role in addressing the model uncertainties to localize the model and thus make the model outputs more realistic allowing their application in developing cities.

Uncertainties, which are the possible unknown forcing in the modeling process, are the motivation behind model calibration to enhance reliability and integrity. Uncertainties usually contribute significantly to the variation between the model predictions and the observed realities of the phenomenon (Liu et al., 2009). In flood modeling, the estimation of the uncertainties is critical to understand how and to what magnitude they cause variations between the model prediction and the observed realities as applied in different geographical areas. In this regard, uncertainties in flood modeling vary from one application to another depending on the input data, the model being used, and the area of study (Todini, 2007). In as much as the sources of uncertainties in flood, modeling may stem from the model design itself and the input data, their estimation and communication instigate some confidence when using the model outputs in critical decision making and thus promote proactive strategies developments in flood risk management.

In as much as model calibrations seek to address the challenges of uncertainties, the significance is to know to what extent a particular model can be applied and yield real results in a particular geographical location within the local contexts of scale and data availability (Todini, 2007). In this case, if a model is to be applied in a developing city, the model is calibrated using the locally available data within the uncertainty boundaries to reach the optimal goodness-of-fit to best and convincingly capture the local context (Bales and Wagner, 2009). In the past few decades, flood modeling literature has been discussing flood inundation model calibration and argues that most models haven't reached the optimal calibration limit. This is partly due to the limited availability of appropriate and reliable calibration data, especially in developing cities. However, the progress in remote sensing data availability is allowing some advancement in flood model calibrations and thus their applications in developing cities (Merwade et al., 2008).

While Model calibration is aimed at reducing uncertainties, a sensitivity analysis that aims at assessing the robustness of the model under various assumptions is also highly recommended. While uncertainty analysis tends to address the impacts of the unknown in the model outputs, sensitivity analysis focuses more on the effects of the known inputs on the model predictions (Aronica et al., 1998). In this regard, sensitivity analysis points out the factors that significantly influence the model outputs, those that need further investigation, and those factors that present a null influence on the outputs (Weichel et al., 2007). Sensitivity analysis, therefore, assists in understanding the sensitivity of the model outputs to the various input variable and factors. Despite its relevance in flood modeling, few studies have been conducted in developing cities and more is yet to be done in informal settlements. While there are questions on the existence and the choice of uncertainty and sensitivity analysis procedure that suits the complexity of flood modeling in developing cities, several methodologies have been reported in various hydrological and flood modeling literature (Koks et al., 2015), (Dottori et al., 2013). Methodologies such as the Bayesian uncertainty estimation, linear regression analysis, and the Monte Carlo Simulations which are based on statistical and mathematical modeling have been used widely in uncertainty and sensitivity analysis of flood models (Hall et al., 2005, 2009). While the choice of the methodologies can be determined by empirical and economic factors, the bottom-line focus on the optimization of the model performance to best inform flood risk management, and therefore the uncertainty and sensitivity analysis play a critical role in flood modeling to evaluate the model behaviors and performance as applied in developing cities (Liu et al., 2009; Bales and Wagner, 2009).

3.5. Flood modelling- the case of Nairobi

3.5.1. Flood risk among the nairobi urban poor

Nairobi is the capital city of Kenya, and about 60% of urban residents are estimated to live in informal settlements. Flooding is a major problem in the city especially in the informal settlements characterized by high poverty levels, unplanned settlements, poor infrastructures such as drainage networks, and poor basic services thus the exposure and vulnerability to flooding risks are high (Dawson et al., 2018). The rapid population increase in the city and the informal settlements have increased by homes built in riparian lands exposing residents to higher flood risk. For example, in Kibera slums, more than 22, 000 residents live along the river banks of Ngong river meandering the city and more than 50% confirm their homes have been flooded in the recent past since 2015 (Mulligan et al., 2019). It can be confirmed that floods are nowadays experienced in areas where the occurrence was rather infrequent two decades ago in the city. The flood risk in the Nairobi informal settlement where a majority of the urban poor dwell is thus eminent to be addressed for the sustainable development of the city (Wamuchiru, 2012).

While city flooding is commonly reported, the impacts are differently felt with the worst hit being the informal settlement and the urban poor. This is a clear demonstration of the underlying drivers of flood risk vulnerabilities among the urban poor. The continuous and rapid change in the land use and land cover due to urbanization has partly contributed to the increased runoff contributing to the city flooding. Despite the evident flood risks in Nairobi and the eminent role flood modeling plays in integrated flood risk management, this review has established that most studies on floods in Nairobi have been focusing on vulnerability and risk perception in parts of the city and less on flood modeling. Besides, most flood studies have been in the past concentrated in the rural areas where riverine flooding has been known to cover a vast area and impacts are closely monitored and recorded.

3.5.2. Flood modeling studies were done in Nairobi

A few studies in Nairobi have been conducted focusing on flood modeling and this is a demonstration that flood models can be applied to simulate the city's flooding characteristics. A study conducted by Muli investigated flood modeling in Nairobi based on the city hydrological processes considering the impacts of rapid urban development (Muli, 2011). The study saw the setting up and calibration of the HEC-HMS model using the available climate and river flow data for Nairobi city as a watershed. The study revealed that the city had a 55% imperviousness then and the increased imperviousness due to increased pavements, buildings, and roads reduces the Soil Conservation Service lag time, and the watershed runoff increases. The correlation between the observed and model-simulated run-off yielded a coefficient of the determinant of 0.82 revealing the model significantly captured the city hydrodynamics. The study also considered different scenarios and revealed that Nairobi city had a 43% chance of flooding after every 2.33 years (Muli, 2011). The impact of an increased imperviousness from 55% to 60% due to rapid infrastructural developments was an increased mean annual flow from 50 m^3/s to 345 m^3/s which is a 600% increment that the existing drainage networks cannot sustain. This revealed a high risk of flooding if the drainage networks are not matched to the increased imperviousness of the city.

Okoth and colleagues 2016 conducted a study on integrated urban pluvial flooding analysis and modeling for Nairobi West and South C areas in Nairobi. In this study, the increased risks of pluvial flooding are reiterated due to the rapid urbanization characterized by urban densification, inadequate city drainage network and continually changing urban hydrology (Okoth et al., 2016). The study employed the use of the Storm Water Management Model version 5.1 using the available GIS data, rainfall, river flow, and sewer network data. The study reveals that significant flooding of 20.134 ha-m surface runoff yields about 81% of sewer system surcharging in the city. A sensitivity analysis of the model shows that the peak runoff significantly responds to variations in imperviousness parameters. The study concludes that the SWMM5.1 model can be applied in simulating urban pluvial flooding and contribute to stormwater and flood management in Nairobi (Hall et al., 2005, 2009).

Urban flood modeling, in most cases, is thought of as an analytical process purely focusing on the empirical inputs and physical processes. Mulligan and colleagues (Mulligan et al., 2019) conducted a study where participatory flood modeling for negotiation and planning in the urban informal settlement of Kibera in Nairobi. While acknowledging the role of analytical methods and hydrological models in flood risk management, the study emphasizes the role of wider stakeholder engagement and contributions in urban flood management, especially in informal settlements. The study develops a new case-based knowledge to inform the application of participatory modeling and planning for informal urban areas. The study uses the newly established framework for the classification of participatory modeling approaches developed by Basco-Carrera and colleagues (Basco-Carrera et al., 2017)and concludes that there are high chances of developing implementable plans and policies for flood risk management when wider stakeholders including those upstream are involved.

There are indications that more flood models are possibly being applied in Nairobi under different ongoing research projects and are yet to be published. More generally, various studies on urban flooding have focused on the vulnerability, exposure, and impacts from the social perspectives and only a few on flood modeling. This review, therefore, points out the gap in flood modeling as a tool in flood risk management in Nairobi, especially in informal settlements.

3.5.3. The role of flood model stacking in understanding city-wide and sub-city flood risks

Mukuru informal settlement in Nairobi City covers almost 650 acres and is home to at least 300,000 people who continually face the risk of urban floods. The Kenyan government has recently adopted the special planning area (SPA) model of slum upgrading where Mukuru was identified as the first SPA in 2017 (Horn, 2021). The model allows coordinated and integrated infrastructural development while improving the service delivery to the residents. Tomorrow's city has been working with the local authorities and partners to promote risk knowledge in the planning and implementation of the SPA in Mukuru. In this regard, there is a need to understand the flood risks in the SPA and integrate this knowledge into the mitigation strategies for a sustainable city (Douglas et al., 2008). Flood modeling that captures the local characteristics at the sub-city level is thus critical. However, the flooding in the informal settlement of Mukuru in Nairobi doesn't solely come from the local area. The city-wide activities, drainage network, rainfall, and settlements among others could be contributing to the flooding in Mukuru SPA. This calls for the city-wide flood dynamics understanding before narrowing it down to the flood dynamics and the underlying vulnerabilities that enhance the flood risks in Mukuru slums.

Model stacking is an efficient ensemble method in which the predictions, generated by using a specific or more model algorithm, are used as inputs in the second layer of algorithms. This framework can be applied in flood modeling in the informal settlement to better-integrated flood risk management (Zounemat-Kermani et al., 2021). For instance, the Tomorrows Cities' research project in Nairobi explores the integration of physical science modeling, social science understanding, and community participation in flood risk management in the implementation of the Mukuru SPA. From this review and application of the framework of model stacking, a combination of flood models has been identified to be applied to achieve the project objectives concerning flood modeling. The Soil and Water Accounting Tool (SWAT) will be used to understand the flood dynamics at the city level using the topographical, climatic, soil, and river discharge data (Kim et al., 2016). The outputs of the model will allow the estimation of floods reaching Mukuru informal settlements from elsewhere in the city. The Hydrologic Engineering Center's River Analysis System (HEC-RAS 2D) model will be used to simulate the flood characteristics within the Mukuru SPA. The combination of the two models at various stages all aim at comprehensively understanding the flood hazard risks in the city and the informal settlement to inform the participatory approach of the SPA model in upgrading the slum towards a sustainable city (Rangari et al., 2019). The local flood characteristics in the informal settlement require a model that can effectively capture the hydraulic networks and the stream geometry while integrating the vulnerability aspects at the local level.

4. Conclusion

While flood modeling is a crucial tool to support effective integrated flood risk management, developing cities and thus informal settlements struggle with their applications due to limited high resolution, accurate and consistent input data for model calibration.

Flood impacts in developing cities which are mostly domiciled in the developing states are most pronounced in the informal settlement and thus the application of flood modeling is a critical component of integrated flood risk management. This practice requires both city-wide and sub-city flood modeling and thus the paper points out the model stacking framework as a method and proposes practices such as nature-based solutions in flood risk management in developing cities (Ferreira et al., 2021). Flood modeling requires very crucial hydraulic flood inundation data among other data sets which are either unavailable, inconsistent, inaccurate, or inaccessible in most informal settlements of developing cities. This trend poses a challenge and perhaps explains partially the limited number of studies in flood modeling in developing cities and more so in informal settlements. However, the urgency to address the prevailing urban flood risks in developing cities supersedes the existing gaps and thus spontaneous studies involving the application of flood models have been conducted.

The advancement in remote sense data coupled with the available although limited ground observed data allows the calibration and application of flood models in developing cities and the informal settlement to inform flood risk management. The review, therefore, concludes that the application of flood modeling in developing cities and informal settlements is possible but requires effective model calibration using the local data to capture the local flow realities and processes, model stacking to understand the city-wide flood dynamics, and advocates for participatory and inclusive practices to address the local vulnerabilities associated with flood risks. Flood modeling is thus an essential technique for ineffective integrated flood risk management in developing cities and informal settlements. The study also suggests further studies in exploring the performance of the different models in various cities with different contexts and focusing on integrated flood risk management. This is because what works for one context may not necessarily work for another informal settlement in developing cities. With the continued impacts of climate change, the study also acknowledges and proposes nature-based solutions in managing current and potential flood risks in the informal settlements of developing cities.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101188.

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