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A review of the current status of flood modelling for urban flood risk management in the developing countries

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ABSTRACT

The prevalence of flooding events and the associated risk in the urban areas is an increasingly important issue of global significance, although it is more critical for the developing countries (DCs), such as Nigeria, where the hazard is often poorly understood and understudied. With current predictions of worsening future scenarios, it is important to pursue integrated flood risk management approaches which incorporate flood modelling. This paper is part of a research programme which is assessing and modelling urban flood risks in the DCs and data poor areas. It focuses on the latest science and philosophy in relation to urban flood risk management in the DCs. It reviews the literature around current flood modelling techniques and provides a comprehensive table of the different approaches alongside the strengths and weaknesses of the different models. Indeed, research in the vicinity of flood modelling has been extensive, and over the years has resulted in the development of a wide variety of schema, datasets and methodologies for simulating flood hydrodynamics. However, the actual potential of these developments has not been demonstrated in the management of flood risk within the DCs. To date, a perfect model or generic technique which can capture every aspect of flood hydrodynamics in an optimal fashion within the diversity of study locations is still unrealistic. Thus, to bypass the present flood modelling challenges within the context of the DCs, extensive calibration of state-of-the-art flood models is of significance. Additionally, researchers within the DCs should be fascinated by the prospect of developing bespoke flood models based on simple mathematical formulations which are easy to parameterise using global, open source and freely- accessible datasets.

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Introduction

The rate at which flooding occurs in recent times has been unprecedented, with the implication that only few coastal, rural, and urban environments still have their natural states unaltered [67,133,151]. This situation is of global significance, although it seems that the perception of flooding in the developing countries (DCs) for example Nigeria, is being nuanced by obvious limitations in research, economy and policy framework [111]. During flooding, water largely covers land areas not usually covered by water, destroying farmland and critical infrastructure, displacing human populations, disrupting economic activities, and in the worst cases, leading to epidemic and death ([135], pg.309). These incidences, especially those relating to fluvial and coastal flooding often were due to sea-level rise, ice melt, overtopping or destruction of water defences and coastal tsunamis [35,93]. However, pluvial flooding, the focus of this review, appears to be widespread in recent times especially within the urban areas where its impacts are increasingly a major source of concern for urban residents and policy makers [38,75,90,152].

Pluvial flooding is basically due to increased frequency and intensity of rainfall, although there are a number of other potential causative factors which have been identified. In Dawson et al. [39] and Adeloye and Rustum [5] pluvial flooding was problematised on the basis of land use change, geomorphology, failure of urban drainage facilities and poor urban planning. Mark et al. [95] perceived pluvial flooding with regards to the scale of its impacts which in fact seem to correlate positively with the large number of human population and development assets within the urban areas. The study demonstrates that urban areas are the hotspot of large-scale flooding impacts to the same degree that they are typically fundamental to any nations' sustainable development. Along with the much-discussed global climate change, which triggers heavy storms in recent times, current knowledge of rapid urbanisation and demographic pressures which characterise the DCs underscores the inclusive nature of urban pluvial flooding, and the primacy of galvanizing discussions for the management of its threats within the DCs [58,156,164,168].

The threat of urban flooding seems immediate for the DCs due to a number of obvious reasons. Firstly, extant studies relating to flood risk management (FRM) in the DCs argue that urban flooding is poorly understood and understudied, and its management measures are either lacking or not adequately put in place [4,45,75,113]. Secondly, the flow of water during urban flooding underscores hydraulic anomalies including jumps and supercritical flows, all of which are difficult to factorise in a general urban FRM procedure [104]. Moreover, many urban centers in the DCs are being covered with impervious surfaces, which reduce infiltration and produce more surface water runoff that can be quite problematic by its nature [29,33,34]. Thirdly, construction of houses along the floodplain, indiscriminate disposal of non-degradable materials, roadside car washing, watering of flowers, coupled with poor or clogged drainage systems are normal anthropogenic activities which heighten the potential of urban flooding in the DCs [6]. Fourthly, alongside the changes in land use/land cover (LU/LC), there is often a lack of space for the rapidly growing human population. As a result, developments take place in increasingly unsuitable locations, leading to relentless evolution of slums which escalate the vulnerabilities of human populations [27]. Finally, the poor knowledge of flooding in most of these areas, makes the extent of the flood impact difficult to predict, and while management of coastal, fluvial and flash flooding has received much global attention (examples: [51,105]), urban flood risk within the DCs arguably has not.

As well as the threats, management of urban flood risk is challenging in the DCs due to the range of sources, to which the hazard is attributed, mostly a combination of physical processes, human activities and the complex geomorphological nature of urban terrain [39,132,143]. Still, the overall aim is to build a resilient city, to minimise human and economic losses [150,145,160]. This implies that as more urban residents in the DCs can adapt to the hazard, the more chances the society has to harness its natural potential towards a sustainable urban development [8]. In achieving this aim, integrated measures, which are driven mainly by the UNISDR philosophy of *'living with floods rather than fighting them'*, are being recommended [57,74]. These measures are targeted to gain a better understanding of urban flood hazard, vulnerabilities and risk in the general sense, to develop robust but low-cost methodologies, and to enhance the availability of good quality flood data [92,98,102]. Within this framework, collaborative governance and community-based approaches towards reducing the impacts of flooding generally have been proposed [155,161]. Integration of urban growth and climate change scenarios into FRM models is cascading from a general understanding that climate change influences the more frequent flooding events through extreme external loadings such as rainfall, while urbanisation escalates the threats of these events [78,124,163].

Within flood risk research, the starting point to a better understanding of urban flooding for its management is formed by the science of hydrology, which in its broadest interpretation relates to water [66,107]. Although everything about water is clearly not the concern of hydrology, the management of water resources and associated risks within the natural environment is underpinned by analyses of hydrological components ([28,66], pg.2). In relation to the propagation of urban flooding in the DCs, it is advisable to factor in the main drivers, which are key hydrological components (examples: precipitation, surface runoff, drainage facilities), and the continuity relationship that exists between these components. This is a crucial research issue which has not been sufficiently discussed within the framework of FRM in the DCs [33,126]. In particular, the drainage system is in poor condition, while reliable intensity-duration-frequency (IDF) models are lacking. The process by which precipitation, which mainly occurs as rainfall, overwhelms soil infiltration capacity and transforms into water surface runoff is still surrounded by much uncertainties [22,70,112].

Over the years, researchers in the field of hydrological science have made significant progress in providing sufficient underpinnings for understanding the theory and practice of urban FRM with regards to the changing precipitation pattern due to climate variations, increased runoff caused by rapid urbanisation and their impacts on urban flooding [65,102,125]. There is now extensive knowledge in the current literature that demonstrates how urbanisation decreases infiltration capacity and the time of peak and increases the rate of runoff and the peak discharge [13,80,89]. The process of runoff and its impacts on environmental systems have been adequately discussed in the literature (see for examples, [165,167,172]. However, these developments did not relate to urban flooding in the DCs. Although rapid urbanisation in the DCs, with considerable part of the land surfaces covered by impervious surfaces, makes urban flooding an exemplar of the whole mechanism which cascades from hydrological science to urbanisation and severe flooding impacts, there is poor knowledge of hydrology to support effective FRM in those areas (Action [2,3,115]).

It is truism that a better understanding and modelling of the relationship between precipitation, surface runoff, urbanisation, climate change and urban pluvial flooding is therefore important in tackling urban flood risks and other water-related problems in the DCs [18]. In theory, the continuity relationship that exists between precipitation input, output and storage is rudimentary to hydrology, and has made significant contributions towards the development of general flood risk management approaches [36,144]. Most of the approaches in the flood hazard literature are based on rainfall-runoff relationship, which often includes urban drainage systems and soil infiltration capacity [23,24,120]. Such approaches require considerable data that reflect both the spatial and temporal variations of the key hydrological components [71,122]. However, as those datasets are increasingly being made available, the lack of technical capacity in the DCs to access and utilise such datasets is a fundamental rationale for the present research, which hypothesises that a proper management of urban flooding for the DCs can be achieved on the basis of improving the understanding of the science of the hazard, and of proven scientific techniques and tools, such as flood modelling.

Best practices in FRM are generally supported by flood modelling, and this can be leveraged within the context of the DCs [90,109]. Conceptually, flood modelling generally involves developing algorithms useful to characterise flooding in terms of flood water depth and extent as well as flow velocity [17]. Since flood water is a form of wave phenomenon that propagates in a down-gradient direction with associated changes in flow rate and water level, these algorithms are often designed to solve the numerical expressions that govern the propagation of flood water from one point to another within a spatial domain [36,116]. Within this framework, there has been significant progress especially in the flood risk assessment and management research, although much uncertainty still prevails in the use of flood models in the DCs [157]. In view of such uncertainty, the calibration of flood model becomes essential towards the actual application of these models [118].

Considering the framework of FRM in the DCs, it is important to understand the suite of potential factors that complicate the implementation of flood modelling techniques. Some general issues have been raised in the literature, and this include the lack of quality dataset - which is now being addressed by a number of global and regional geospatial data development programmes - uncertainty in model assumption and simplifications, as well as diversity in the conceptualisation of risk and its essential components [64,71,102,114]. However, there are some potential specific issues, which are sources of uncertainties and knowledge gaps and these have not been adequately researched, hence this review which considers the latest developments in the literature in relation to flood modelling towards addressing the risk of urban flooding in the DCs. The key aim is to investigate the poor implementation of flood modelling for urban FRM in the DCs. 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 urban areas of DCs. It advances previous reviews such as those of Ne'elz and Pender [109] and Teng et al. [142]. This is an apt time for a review of the literature as advances in flood modelling have evolved rapidly in recent years and are now a central concern in various attempts to mitigate flood hazard. The novelty of the present review is the context-specific discussions that are aimed to support flood modelling in the DCs. The review concludes with a detailed list of current flood models and discusses the challenges and prospects for the future of urban flood modelling.

Urban flood modelling within the DCs

Modelling of urban flooding from pluvial events that occur in the DCs has not received sufficient attention. As well as being an emerging phenomenon in the flood hazard literature, urban pluvial flooding in the DCs is essentially characterised by a few underlying factors, which seem to constitute limitations and knowledge gaps towards its analyses within the context of the DCs. Firstly, the means to represent the hydrological, climatic and anthropogenic factors which drive urban flooding in these areas are complicated, especially in formulating and solving the shallow water equations (SWEs) which lies at the foundation of flood modelling [96,117,132]. Secondly, urban geomorphology in the DCs intersects with flood hydrodynamics, and to represent this situation in a realistic fashion within the flood model requires detailed topographic data such as LiDAR (Light Detection and Ranging) digital elevation model (DEM), and this is still not fully accessible for many urban catchments in the DCs [171]. In the case of pluvial events, finely-gridded precipitation data often required to parameterise these models do not exist in the DCs. Thirdly, similar to fluvial and coastal flood modelling, it is still expected that an urban pluvial flood modelling methodology should be able to address the issues of conditional stability, high computation cost and uncertainties. So far, solutions to these issues have overwhelmed the research and knowledge potential within the DCs.

Indeed, some progress has been made towards improving the status of flood analyses and monitoring within the DCs. This is potentially due to the ratification of various global disaster initiatives, particularly the UNISDR global flood partnership (GBP) anchored of five essential pillars to effect positive results in flood management and resilience globally [41]. In line with this objectives, the African regional data cube (ARDC), Africa GeoPortal, digital earth Africa (DE-Africa), the global partnership for sustainable development data and group of earth observation (GEO) recently launched a new scheme, promoting the provision and utility of quality geospatial data and tools and skill acquisition for five African countries: Kenya, Sierra Leone, Ghana, Tanzania and Senegal [101]. Impetus to achieve the sustainable development goals (SDGs) is another improvement that is driving various initiatives and innovations in research and feasibility studies towards improved flood analyses for the DCs. There has been an increase in community participation towards flood risk management, as well as improved knowledge of flooding through various research agenda within the African region and the DCs. Social media and popular culture such as the TV, internet, cinema and CCTV are also part of the improvement, which bears heavily on simplifying the validation and calibration of existing flood models for the DCs [7,52,84,114,136]. It is expected that these critical geospatial innovations, particularly the ARDC, will be able to exploit various the up-to-date earth observation satellite imagery to address current environmental and socio-economic issue within the African region. However, the limited availability of data and limited access to data are still prevailing issues which now prompt the need for enterprise investment and political discussions. Differentiation or variation in accessibility of geospatial data in particularly Africa and the DCs *vis-a-vis* the rest of the world in general is pertinent to research. Within this framework, one would notice easily that the DCs are poorly represented within a global context of geography of data access. This idea is being proposed as a new frontier and direction for research into flood analyses within the DCs.

In particular, the ARDC initiative is arguably a key spotlight for the present review, and is being recognised as a great prospect towards addressing the key issue with data and technical-know-how for key environmental issues which include flooding within the DCs. However, there is are limitations and critical issue which still prevail in view of this innovation within the DCs. Firstly, ARDC is a great innovation for data infrastructure within Africa, but the present review is not only about Africa, it considers the DCs in general. This means that a good idea of data coverage for the DCs should contemplate the means to densify such a critical geospatial data cube infrastructure in other DCs within the Asian and Caribbean regions. Secondly, despite the potential within the ARDC, the overall scope of availability of this geospatial dataset is still limited in the meantime, and this is an issue of research interest. While the dataset cube is only presently available for five countries within the African region, the reality that the rest of the other forty-nine or so other African countries do not benefit from and leverage such an ultimate enterprise involving satellite data infrastructure to optimise flood modelling is a major limitation which is relevant for both research and political discussions. As a result, further research will have to consider the geographical differentiation of data availability which seems to be another critical issue with respect to access to these data for FRM research.

In addition to these developments, the European Space Agency (ESA) through the recently launched *Sentinel* satellite family is now providing near real-time to real-time radar based satellite images for flood hazard mapping and monitoring and for validation and calibration of numerical and hydrodynamic flood models [77,83,149]. The idea of *Sentinel-1* satellite data as crucial for any review of flood risk modelling and analyses within the context of the DCs is unassailable. As an open data, *Sentinel-1* offers a world of potential and possibilities for the DCs and data poor communities. Research is still developing towards the utility and functionality of this scheme. Looking at the current literature, much discussions have been presented with developing topical issues on the wide-ranging applications of these dataset for flood monitoring, mapping, and calibration of hydraulic and hydrologic flood models [86,88,127]. However, there is little knowledge of this dataset in many of the DCs, and the internet-of-things (in terms of high speed broadband and portable servers) needed to access these dataset is lacking. The lack of technical capacity and poor infrastructural development needed to access, archive, operationalise and leverage these *Sentinel-1* geospatial data infrastructure are still issues to be addressed within many sovereign states in the DCs [41,56].

These issues are fundamental to the epistemological foundation of the present review while it contributes to the science of FRM within the DCs. Besides supporting the understanding of the current development in flood modelling research in relation to these limitations and knowledge gaps, the present research reviews undergirds the realisation of the intrinsic behaviour of existing state-of-the-art flood models so as to motivate research into the means to assuage current challenges in flood modelling in the DCs.

In reviewing these flood models, the authors adopted a model classification scheme as the starting point. Although there has been no homogeneity in classification of flood modelling methods, for the purpose of this review, classification has been based on spatial extent, dimensionality and mathematical complexity (see Fig. 1). This classification is intended to shed some light into the methodologies and main assumptions involved in developing the models and how their applications within the DCs have been constrained. More detailed and seminal discussion of the classification criteria for flood models can be found in Knapp et al. [81] and Todini [146]. Based on this classification scheme, Table 1 provides a list of some known flood modelling tools, applicable to flood risk assessment. With the exception of SWMM (Storm Water management model) first proposed in 1971 by the United States Environmental Protection Agency (USEPA), the table was meant to show relevant flood models developed forward from 1990. This is to limit our review with recent model within the current literature. However, due to its compelling importance in a myriad of hydrologic and hydraulic operations, and the extent to which it has been presented in extant research and discussed in the current literature (for examples [53,99,110]), SWMM has been included in the table. It can be inferred from Table 1 that there is no perfect flood model. As well as being able to simulate flood hazard, these models have limitations, which undermine their versatile applications, especially the DCs urban environments, and this is one of the main rationale for focusing on the review of flood modelling techniques in the present research.

Regardless of the categorisation of existing flood models, recognizing those factors which constrain the application of existing flood models within the DCs is of research importance. In line with this objective, the most part of our discussion focused on models that are classified based on dimensionality. Existing flood models of this type are categorised as one-dimensional, two-dimensional and three-dimensional flood models [17,50,59,134]. One-dimensional flood models such as

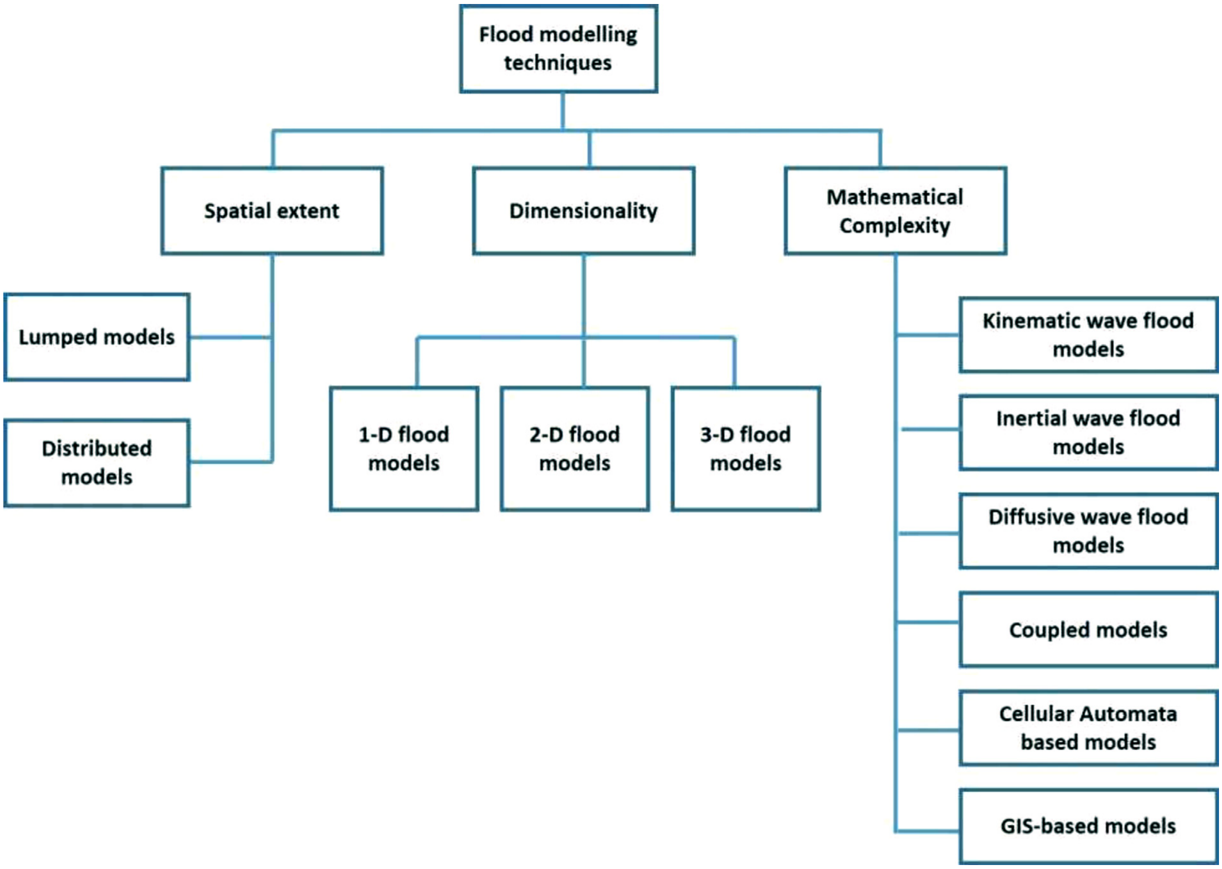

Fig. 1. Classification scheme of flood modelling methodologies.

ISIS, MIKE 11 and HECRAS represent the channel and floodplain as a series of cross-sections perpendicular to the flow direction and solve either the full or some approximation of the one-dimensional SWEs [14]. They are the simplest of all flood models, computationally efficient and lend themselves easily to parameterisation using traditional field surveying, without necessarily requiring distributed topographic and friction data [14]. The simplicity of one-dimensional models is a result of significant neglect of important aspects of flood hydraulics, which often characterise urban flooding in the DCs [59,68,69]. Whilst their key merit is limited data requirement, one-dimensional models are characterised by severe limitation in their representation of hydrological processes [134]. As a result, they cannot conveniently simulate urban flooding in the DCs.

Several efforts have been made to enhance the predictive capacity of the one-dimensional flood models, but so far it is obvious that these efforts are still far from a satisfactory application of these models in simulating urban flooding within the DCs. For example Mark et al. [94] used a one-dimensional flood model coupled with buried pipe system, street network and the areas flooded with stagnant water to simulate a realistic urban flood inundation for cost-effective planning and management of urban drainage system. Despite the contribution which the study makes to the science of flood modelling, its main uncertainty - which highlights the critical issue with modelling urban pluvial flooding in the DCs - lies in the treatment of the street topography and of flow in one dimension.

The two-dimensional flood models such as TUTFLOW, SOBEK and MIKE 21 solve the two-dimensional SWEs by means of appropriate numerical schemes [1,47,104,137]. Advances in remote sensing technology (especially through high resolution and high accuracy input data such as airborne LiDAR and Synthetic Aperture Radar (SAR) data) and improved computing capacity seem both to have increased the popularity of two-dimensional models [166]. Apel et al. [9] and Arrighi et al. [10] argue that high-resolution topographic data impose rigorous effects in two-dimensional flood modelling involving accurate delineation of urban geometry such as street, roads and building. To simulate urban flooding, 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 [17,158]. However, to apply such a model in the DCs without having such high-resolution topographic data and high end computing facilities would necessitate a compromise in grid resolution, and consequently eke out the uncertainties in the model output. This is a major limitation, which is crucial to FRM research within the DCs. Two-dimensional flood models are increasingly being applied in the

Table 1
Summary of flood modelling tools available in the current literature.

S/no.	Author(s) (Date)	Model name	Model Type & Dimensionality	Main Assumption	Mathematical Framework	Numerical Solutions	Access	Strengths	Limitations
1.	Army Corps Of Engineers (ACOE) (1995)	HEC-RAS	1-D Hydraulic	Basically, the model solves the one dimensional energy equation for steady flow. However, it can solve the full 1D shallow water equation for unsteady flows.	One-dimensional energy equation to solve for friction and contraction	Implicit finite difference solution	Open source. However, user assistance is limited to ACOE users.	Extensive documentation, suitable for a wide-range of data quality, easily adaptable and easy to set up.	Model instability and limitation in environments that require multi-dimensional modelling.
2.	Army Corps Of Engineers (ACOE) (1992)	HEC–HMS	Hydrologic	Primarily designed to simulate the precipitation run-off process of dendritic drainage basins. Also capable of solving a range of hydrologic problems	Different statistical and mathematical concepts describing physical processes are used in modelling.	Analytical solutions of underlying mathematical representation of hydrologic processes.	Open source. However, user assistance is limited to ACOE users.	Extensive documentation, suitable for a wide-range of hydrologic applications and amenable for integration with other software.	Would generally fail under dynamic flood simulation conditions.
3.	Halcrow, (now CH2M HILL) (2009)	ISIS-2D	2-D Hydraulic	Designed to work either standalone or within the ISIS suite	Full two-dimensional shallow water equations	Alternating Direction Implicit (ADI) , FAST and Total Variation Diminishing (TVD)	Commercial	Wide range of clientele. Suitable for hydrodynamic flood simulation.	Slow simulation speed and requires a high resolution topographic data.
4.	Halcrow (now CH2M HILL) (2008)	ISIS-1D	1-D Hydraulic	Designed primarily for modelling water flows and levels in open channels and estuaries.	Full one-dimensional shallow water equation	Muskingum-Cunge scheme for steady state and 4-point Preissmann scheme for unsteady state.	Commercial	Suitable for steady, unsteady, subcritical, supercritical and transitional flows	Assumes velocity normal to cross section and not suitable for dynamic flood simulation
5.	Halcrow (now CH2M HILL) (2009)	ISIS - FREE	Coupled 1-D/2-D Hydraulic	Provides an advanced one-dimensional (1D) and two-dimensional (2D) simulation engine, analysis and visualisation tools.	One-dimensional and two-dimensional shallow water equations.	Alternating Direction Implicit (ADI) , FAST and Total Variation Diminishing (TVD)	Open source	Suitable for wide range of applications including urban areas, coastal and river channels.	Limited to 250 1D nodes and 2500 2D cells.
6.	Halcrow (now CH2M HILL) (2011)	ISIS-FAST	Simplified 1-D / Simplified 2-D	Quick simulation of flooding using simplified hydraulics	Simplified shallow water equations	FAST solvers	Commercial	Simulation speeds are up to 1000 times quicker when compared to traditional 2-D flood models	Requires high resolution data and is commercial software.
7.	Bates and De Roo, [14]	LISFLOOD-FP	Simplified 2-D	A raster-based hydraulic model that is assumed to possess the simplest hydrologic process representation.	One-dimensional Kinematic and two-dimensional diffusive wave equations.	Explicit finite difference solution.	Research	Extensive documentation, easily adaptable and simple to set up	Requires a high resolution topographic data for simulation.

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Table 1 (*continued*)

S/no.	Author(s) (Date)	Model name	Model Type & Dimensionality	Main Assumption	Mathematical Framework	Numerical Solutions	Access	Strengths	Limitations
8.	De Roo, A.P.J., Wesseling, C.G. and Van Deursen, W.P.A. (2000)	LISFLOOD	GIS-based distributed hydrologic model	LISFLOOD is a GIS-based hydrological rainfall-runoff-routing model.	One-dimensional Kinematic wave equation	4-point implicit finite difference solution and analytical solutions of other hydrological components.	Research	Wide range of applications including simulation of interception of rainfall by vegetation, evaporation of intercepted water and Leaf drainage.	Not a stand-alone code. It requires a base platform of PCRaster modelling environment.
9.	DHI (1997)	Newer MIKE 11	1-D Hydraulic	Developed to simulate flow and water level, water quality and sediment transport in rivers, flood plains, irrigation canals, reservoirs and other inland water bodies	Full one-dimensional Saint Venant equations, diffusive and kinematic wave approximation	Muskingum method and Muskingum-Cunge method for simplified channel routing	Commercial	complemented by a wide range of additional modules and extensions covering almost all conceivable aspects of river modelling	Limited to rivers and fluvial-related flood events. Model can be unstable under two-dimensional flood conditions.
10.	DHI	MIKE 21	2-D	Developed to simulate flows, waves, sediments and ecology in rivers, lakes, estuaries, bays, coastal areas and seas in two dimensions	Full 2-dimensional shallow water equations	Implicit finite difference techniques with the variables defined on a space-staggered rectangular grid.	Commercial	Suitable for hydrodynamic flood simulation. Simulates bulk flow characteristics, flow velocity in various directions of flow.	Simulations time steps and model stability are affected by C-F-L condition. Needs to be calibrated.
11.	DHI (2007)	MIKE-FLOOD	Coupled 1-D/2-D Hydraulic	Developed to enhance the independent functionalities of MIKE 11 and MIKE 21	One-dimensional and two-dimensional shallow water equations.	Coupled solution of 1-D/2-D shallow water equations.	Commercial	Satisfactory real-time simulation of flood inundation in river, coastal and urban areas.	Not well adapted in terms of application to many places. Models requires calibration
12.	BMT-WBM (1990)	TUFLOW – 1D	1-D	Simulation of complex hydrodynamics of flood using full 1-D St. Venant equations.	Full one-dimensional shallow water equation	Second order Runge–Kutta finite-difference solution	Commercial	Dynamic linking capability between domains. Fast from computational point of view.	There are uncertainties in solution and are poor at process representation.
13.	BMT-WBM (1997)	TUFLOW – 2D	2-D	Simulation of complex hydrodynamics of flood using full 2-D free surface shallow water equations.	Full two-dimensional free surface shallow water equations	Stelling Finite Difference and ADI	Commercial	Dynamic linking capability between domains. Satisfactory representation of process.	Slow, but dynamically captures bulk flow characteristics.
14.	JBA Consulting (1998)	JFLOW	Simplified 2-D	Designed to address the challenge of process representation. It is basically a simplified physics flood model.	Diffusion wave equation	Explicit finite difference scheme	Commercial	More accurate flood simulation and simple to set up and useful at coarse resolution.	Conditional stability through the C-F-L condition. Unable to account effects of small scale features during flood simulation.

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Table 1 (*continued*)

S/no.	Author(s) (Date)	Model name	Model Type & Dimensionality	Main Assumption	Mathematical Framework	Numerical Solutions	Access	Strengths	Limitations
15.	Cardiff University R. Falconer	DIVAST(depth-integrated velocities and solute transport)	2-D	Solution that includes the effects of: local and advective accelerations, the earth's rotation, free surface pressure gradients, wind action, bed resistance and a simple mixing length turbulence model.	Full 2-dimensional shallow water equations	Implicit finite difference technique and the ADI formulation.	Commercial	Unconditionally stable. Constant time steps	Lacks the ability to capture shock resulting from simulation.
16.	Cardiff University	DIVAST- TVD	2-D	To address some limitations inherent in the original DIVAST model.	Full 2-dimensional shallow water equations	TVD-McCormack explicit finite difference scheme	Commercial	Ability to capture shock	Conditional stability
17.	Deltares	SOBEK	2-D	Specially designed for Overland Flow	Two-dimensional Saint-Venant equations	Finite difference Scheme. By means of a rectangular grid	Commercial	The model is capable of handling wetting and drying, spatially varying surface, roughness and wind friction.	Conditional stability
18.	Deltares / Delft Hydraulics	SOBEK	1- D	Specially designed for Rural, Urban and River flows.	One-dimensional Saint-Venant equations	Finite difference Scheme.	Commercial	Breaches can be modelled by means of a complex "river weir" with time dependent properties.	Conditional stability
19.	Électricité de France. (EDF) (2010)	TELEMAC	2-D	Designed to address the challenges of process representation and limitations in channel and floodplain flood modelling	solves the full two-dimensional shallow water equations	finite-element or finite-volume method and a computation mesh of triangular elements	Open source	It can perform simulations in transient and permanent conditions	Conditional stability
20.	Électricité de France. (EDF) (2010)	TELEMAC	3-D	To address some limitations inherent in the 2-D version of the model	Navier-Stokes equations, whether in hydrostatic or non-hydrostatic	finite-element or finite-volume method and a computation mesh of triangular elements	Open source	Ability to capture 3-D hydrodynamic features of an area. Suitable for all flood sources	Conditional stability
21.	Nottingham Uni.	TRENT	Full 2-D	A flood model that is able to capture full hydrodynamic properties.	Shallow water equations	Explicit Finite difference scheme	Commercial	Shock capturing ability	Stable at CFL condition, using adaptive time stepping.
22.	Martin and Gorelick [169]	MOD_freeSURF 2D	2-D	To obtain a more efficient flood simulation through a more robust numerical scheme.	Unsteady state Shallow water equations	Semi-implicit, semi Lagrangian numerical scheme.	Open source	Modularity, computational efficiency and minimum data requirement	Lacks extensive validation.

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Table 1 (*continued*)

S/no.	Author(s) (Date)	Model name	Model Type & Dimensionality	Main Assumption	Mathematical Framework	Numerical Solutions	Access	Strengths	Limitations
23.	Ghimire et al. [55]	CADDIES	2-D	A model that performs optimally at simulating flooding in urban areas.	Rules that govern movement of water in-between cells	Cellular automata	Open source	Fast simulation of flooding	Lacks extensive validation.
24.	Jimmy S. O'Brien	FLO-2D v. 2007.06 and 2009.06	Simple 2-D	Hydrodynamic model for the solution of the fully dynamic equations of motion for one-dimensional flow in open channels and two-dimensional flow in the floodplain.	Full 1-D and 2-D shallow water equations.	Finite difference solutions	Commercial	A combined hydrologic and hydraulic modelling for urban and river flooding.	Bridge or culvert computations must be accomplished external to FLO-2D using methodologies or models accepted for NFIP usage.
25.	Chen et al. [33]	GUFIN (2009)	Simplified model	A model that simplifies the use of distributed models for urban environment	GIS- based	GIS and infiltration functions	Research	Integrates GIS and quite suitable for urban flooding. Results compares well with numerical codes.	Lacks extensive validation.
26.	DHI Water and Environment	MIKE URBAN 2010	Coupled 1D and 2D	Has the capability to analyse storm sewer networks. Flow conditions associated with weirs, orifices, manholes, detention basins, pumps, and flow regulators can be reflected.	1-D unsteady flow	Implicit, finite difference numerical scheme.	Commercial	Suitable for flow in urban areas. Integrates GIS capabilities.	Lacks the ability to capture some hydrodynamic phenomenon such as shock and supercritical flows.
27.	SWMM, new versions.	USEPA (1971–2005)	Generic	Designed to represented six major environmental components: external forcing, surface runoff, groundwater, conveyance system, contaminant built-up and (LID) controls.	Kinematic wave model Full dynamic wave system.	Generally the finite difference scheme	Open source	Extensive documentation. Several upgrades and adaptive to a range of hydrological and hydraulic operations - urban flooding, drainage, etc.	The model required many add-ons, and a user needs to understand the detailed guideline.

prediction flood of all sources and so far accounts for the optimal performance achieved in flood modelling, although the lack of rigorous model calibration still constrains the application of these models in the DCs.

The three-dimensional flood models solve the full *Navier-Stoke equation*s and consider flow of flood water as completely three-dimensional [109]. Indeed, to be able to dynamically represent the physics of water flow, especially in the urban areas of the DCs, it is worthwhile to apply the three-dimensional model [17]. Nevertheless, some authors have argued that such a model would be unnecessarily complex, if some assumptions can lead to simpler models that would offer realistic solution ([69]; Hunter et al., 2008). Similar to the two-dimensional models, practical actualisation and application of the three-dimensional models for urban FRM within the DCs have been largely constrained by the geographic differentiation in the availability of high resolutions datasets, unavailability of high-end computing facilities and limited external calibration of existing three-dimensional models [112].

A vital factor that must not be overlooked in reviewing flood models from the perspective of dimensionality is the numerical schemes or formulations which are fundamental in enhancing the scope of flood modelling functionality [140,153]. Of course the lack of an exact solution to the SWEs and their simplifications gives rise to numerical formulations, which form important aspects of flood modelling procedure [15,37]. In practical application, these formulations are often evaluated by *discretisation* of a meshed topographic surface. This highlights the importance of quality datasets in modelling urban flooding and the likely implications for areas with data sparse situation. Over the years various numerical schemes have been formulated to solve a variety of hydrodynamic problems especially in the computational mathematics and flood modelling literature [15,31,87]. However, there is no clear research evidence indicating that existing numerical flood models have been sufficiently applied to simulate urban flooding in the DCs and data poor areas.

In most of the developed societies, some of the widely applied numerical schemes include the characteristics schemes, explicit and implicit finite difference schemes, semi-implicit finite difference schemes, finite element, and finite volume numerical schemes [1,26,32,49,54]. The growing ideology that underlies these developments is the provision of an unconditionally stable hydrodynamic solution within a relatively convenient computation cost [32,141]. Despite these developments, existing numerical schemes have not reached the expectation of accurate prediction of flood inundation in a variety of urban environments. Whilst there has been little research in respect of numerical schemes and their implementation within the context of the DCs, the quest for a proxy numerical scheme that can achieve an optimal performance in flood simulation, model stability and computation cheapness as well as to meet the challenges of flood modelling in the DCs still lingers.

The next category of flood models considered in this review are those based on simple mathematical complexity. Within this category, majority of the existing flood models are built upon the hypothesis that *'an ideal model should be simple and able to provide the required information whilst reasonably fitting available data'* [71]. Based on this assumption, a good number of flood models have been proposed in recent times. However, there is still much gap in the current literature, in relation to the development of an ideal model and how to meet the increasing challenges of urban flooding particularly within the context of the DCs and data sparse localities [153]. In spite of some limitations associated with models that exist currently in this category, their contributions over the years towards mapping and assessment of flood risk have been significant [43]. This is despite the limited availability of quality data in many environs, the complexity of many urban environments and the accuracy requirements of flood modelling. For example, whilst there are clear justifications for model simplifications, the limitation placed by poor representation of flow characteristics constrains the applications of these models for simulating flood inundation in complex urban environments of the DCs [71]. Moreover, due to poor model calibration, driven by lack of parameterisation data, and sensitivity analyses, transferability of flood models to external locations is often constrained [51].

Critically, the simplicity of flood models is a function of the hydraulic processes represented in the model. This is very crucial for flood modelling in the DCs. As a minimum, friction, slope, acceleration, gravity, mass and momentum should be represented by an optimal flood model [37]. Unfortunately, the question of how to resolve the representation of these processes in an optimal and dynamic fashion in a model with regards to required model accuracy and availability of input data remains largely debatable and so far unrealistic particularly in the DCs [69,72,105]. Besides the required model accuracy and availability of input data, it is equally important that decisions regarding the processes to be represented in a flood model are informed by the nature of flood hazard and uniqueness of the flood-affected locations.

Majority of the models in the category of mathematically-simple flood models are the simplified two-dimensional models or reduced complexity models (RCM) such as the LISFLOOD-FP, JFLOW and ISIS-FAST [14,158]. Along with other raster-based flood models, coupled 1D/2D models and Cellular Automata (CA) based models, RCM solve the kinematic wave, diffusive wave and inertial wave equations which result from various simplifications of the SWEs [71,122]. These models have so far provided realistic applications in the areas of urban flood modelling, although they still raise critical issues in modelling urban flooding within the DCs [15,90].

In particular, the CA-based flood models are increasingly gaining recognition in recent times [46,90]. To simulate flood inundation, the *CA* based flood models use transition rules on a discrete space within specified neighbourhoods [55,128]. Simple process representation is the main hypothesis underlying this class of flood models, whilst they seem to present less of a computational burden at variable resolution, and attempt to overcome those limitations inherent in the one-dimensional, full two-dimensional and three-dimensional flood models (Hunter et al., 2008). Despite clear evidence of the contribution these models have made is the myriad of scientific discussions which they triggered in the body of literature, there is little investigation regarding their application in FRM within DCs.

Throughout the literature relating to RCM, debates are still on-going regarding the degree of reduction in the SWEs, modelling of wetting and drying, treatment of source terms, and formulation of optimal numerical solutions and improvement of neighbourhood framework within the *CA* formulation and this is key to meeting the challenges of flood modelling in the DCs [15,55,100,106,108,148]. Recently, Nkwunonwo et al. [114] proposed a new flood model, which combined semi-implicit finite difference scheme and *CA*. Although the model performed optimally at simulating a historical flooding event that occurred in the Lagos metropolis of Nigeria, sufficient sensitivity analyses are needed to validate some assumption made in the model. These are issues that currently assuage expected application of the RCMs within the context of the DCs.

Calibration of flood models

It is truism that existing models, regardless of the spatial extent, complexity and dimensionality, posses both strengths and limitations, which make then unsuitable for use in places such as the DCS where the impacts of flooding are arguably disproportionate. Nonetheless, flood modelling is still at the heart of flood risk management, and so research is now fixated on the means to accomplish this objective despite the current data and science challenges that confront these economically-disadvantaged areas. As a potential measure, calibration of existing state-of-the-art flood models using context-specific and generic datasets is being considered in the current literature [48,82,138,142]. This review now considers such a measure in terms of what potential it may have towards actualizing flood modelling in the DCs.

In considering the potential of calibration process to enhance flood modelling in the DCs, it is important to note that discussions such as this usually climax with the concept of uncertainties or systematic errors which need to be determined and incorporated in the modelling procedure to make sense of the final result. Uncertainties are crucial within the scientific community and indeed fundamental to the current review of flood modelling for urban FRM in the DCs. Actually, urban FRM in the DCs is dazzled by the presence of uncertainties in data, method, the theory that undergirds the whole spectrum of FRM, and these undermine the accuracy and reliability of research and technical efforts. This pushes approximation boundary backwards, so that the expectations of quality and standard will be unrealistic for the DCs [25]. The majority of research relating to flood modelling reports the presence of uncertainties in existing flood models [48,153,162]. There is a great possibility that this model would complicate the present situation in the DCs if they are applied without addressing these uncertainties. Therefore, the need to manage uncertainties in urban FRM within the context of DCs is an important research issue which is being factored into this review.

Primarily, uncertainties - which are the major motivation for model calibration - are unknown possibilities that accompany models which need to be found in order to assess the level of model's reliability and integrity [91,120]. They sometimes account for the variations between model predictions and observed or real world data [51]. The ubiquitous nature of uncertainty in flood hazard prediction and flood risk assessment and the need for its estimation and communication to other professionals and decision makers is now widely acknowledged [63,119,123,147]. In flood modelling, estimation of uncertainties is a crucial stage of work to understand these variations and how they affect model application in external locations using the DCs as a case in point [16]. Whilst the sources of uncertainties in flood modelling principally include the design of the model itself, parameters that are considered and the input data [103], the communication of their estimates assures confidence when using the models in decision making and promotes proactive strategies and measures towards flood risk management [63,76,142].

Calibration of flood model is somewhat a procedure to address the challenges of uncertainties. It seeks to find appropriate values, which will ensure that model yields realistic predictions irrespective of geographical locations [73,118]. The significance here is to know to what extent a model can be applied to other geographical location within the context of scale and availability of input data [154]. If a model is to be applied to the DCs, in the calibration procedure, the model parameters are adjusted within the boundaries of uncertainty to reach a goodness-of-fit in model prediction of reality [97]. Since the last two decades, several attempts to calibrate flood inundation models have been extensively discussed in the flood modelling literature [21,44,85,97], although it is still being argued that existing flood models have not reached the acceptable calibration limit [51,71]. This is due to the limited availability of appropriate calibration data, which has a critical concern in flood modelling, flood risk assessment research, but also in a wider application of existing flood models for assessing human, environmental and economic impacts of pluvial flood inundations in the DCs [15,19,73,139].

At present, progress in remote sensing technology is increasing the availability of appropriate data for model calibration [17]. However, within the poor localities of which the DCs are examples, the cost of acquiring these data and other technical considerations remain major challenges to full utilisation of remote sensing technology in order to harness the potentials of model calibration. However, studies are still underway towards the means of addressing this present limitation, which seems to inform goals of many flood modelling exercises [15,33,40,131]. No study to the authors' best knowledge has provided the means of addressing these limitation and gaps within the DCs, to enable application of ensemble, research and open source flood models. Although actual calibration was not carried out in the present review, it is still an important discussion towards a critical understanding of the causes and implications of limited applications of flood modelling in various case studies within the DCs which is the basis of the present review. Consequently, given the urgent need to improve flood risk management in the area, a logical alternative is the development of a bespoke flood model that will take advantage of easily accessible datasets, and this is what the present review argues about.

In addition to calibration of flood models to reduce uncertainty, researchers also suggest sensitivity analysis to assess how robust a scheme is to varying assumptions [11,19,20]. While uncertainty analysis is typically a direct problem, that is can applied in situations where quantities in a system under analysis are precisely unknown or need to be determined, however, sensitivity analysis can be thought of as addressing the inverse of a problem and in revealing the effects of model input variables on the overall variation in the model prediction [60]. It identifies the factors that demonstrate the most significant influence on model output, those that show null contributions and those that may need further investigation to improve on their contribution to the model [62,63]. Uncertainty analysis involves estimation of uncertainties in model inputs and apportioning them to model predictions [61]. Sensitivity analysis assists with the understanding of the performance of a flood model to various parameters, for example topography and Manning's friction coefficient [16,129]. It generally examines how the variation in model prediction can be apportioned to different sources of variation [30]. Although sensitivity analysis, to a greater degree, can extend the application of existing flood models to the DCs, there has been little research in this area, and existing flood models have been limited to locations with sufficient calibration datasets.

Uncertainty and sensitivity analyses are now routine procedures that provide a general basis for evaluation of model behaviours and performance and the possibility that it can be adapted to urban FRM in the DCs [12,120]. Within this context, a major concern is the lack of uncertainty and sensitivity analyses procedures that possess the robustness and complexity which can match with existing flood inundation models [42,62]. Over the past two decades a number of methodologies for sensitivity and uncertainty analyses have been reported in hydrological engineering and flood modelling literature [60,119]. These approaches (for example, Bayesian uncertainty estimation, Generalised Likelihood Uncertainty Estimation (GLUE), Monte Carlo Simulations (MCS) and Linear regression analysis) are based on complex statistical analyses and rigorous mathematical modelling [12,159]. Whilst there are special considerations for using a particular methodology, Hall et al. [62] reviewed a range of existing methodologies for sensitivity analysis and indicated that there are potentials and limitations associated with various existing methodologies. Whilst the choice of methodology can be based on empirical and economic factors, limitations in sensitivity analyses can often lead to misleading conclusions, which fail to replicate the actual model behaviour [62]. Although these considerations and choices in methodology can bear on the expectations of promoting flood modelling for urban FRM in the DCs, a more epistemic issue lies with how these procedures can be used to enhance flood modelling in the DCs, and this is one of the objectives of this review.

Conclusion – the challenges now for flood modelling?

Flood modelling is a crucial tool in developing policies for flood risk management. As discussed extensively in the literature, there is frequently a situation that ranges from total data paucity, lack of access, to limited availability of high resolution data to use in models. This is not always an issue in developed countries such as Netherlands, United Kingdom and the United States, but for the developing countries (DCs) especially in Asia and Africa, this represents a significant barrier. The reason for this uncertain situation of information may range from a lack of funds to political influence (Action [2,151]). This situation is particularly true in relation to hydrologic and hydraulic flood inundation data, which are characterised by flood depth, inundation extent, inundation time and water flow velocity. Topographical data are also crucial, and should also be of a high resolution and offer the spatial domain for assessing flood risk and are useful for extracting variables for flood model calibration. In general, they are key variables needed for estimating the impacts of flooding events and the likelihood of its occurrence.

Although geospatial advances and remote sensing technology now offer a viable tool to address this data challenge, the cost of airborne or space borne data acquisition, expertise in data processing and software requirements can be overwhelming for the DCs and data poor localities. Although many flood risk assessments and mitigation measures have resorted to flood modelling for simulating flood data, there are still peculiar issues that assuage the use of existing flood models within the context of flood risk management in the DCs. Globally available topographic data such as Shuttle Radar Topographic Mission (SRTM) and Advanced Space-borne Thermal Emission and Reflection Radiometers Global Digital Elevation Models (ASTERGDEM) have often served as substitutes for high resolution topographic data [170]. The concern in using such global datasets in the highly urbanised DCs is the horizontal and vertical accuracies which are not good enough to accurately estimate flood inundation or yield realistic model calibration results.

There is also often a lack of detailed information in relation to flood frequency analyses and extent. The aim of flood frequency analysis is to relate the magnitude of extreme flood events to their frequency of occurrence through the use of probability distributions and various methodologies exist in the current literature [36,79,130]. Within the global context, proliferation of mathematical models which seem to lack theoretical hydrological justification is the key concern in flood frequency analysis [79]. However, within the context of the DCs, lack of a reliable intensity-duration-frequency (IDF) model is a major limitation. This constrains the application of flood frequency analyses in any flood inundation estimation procedures.

Reduced complexity flood models including the kinematic wave, diffusive wave, and inertial wave equation, along with GIS-based, Cellular Automata (CA) based flood models have proven to be viable alternatives to the highly intractable shallow water equations (SWEs) in terms of reduction in computation time and unconditional stability [33,121]. However, these hybrid models still need further enhancement to establish their potentials and usefulness in the DCs. Research involving the CA based models is still emerging, whilst the integration of numerical schemes into CA formulation is being proposed [114]. These models also have not been extensively validated, suggesting that whilst the level of uncertainty in their usage is both significant and not well known, adapting such flood models in the DCs is debatable.

With the increasing availability of global flood risk model, one would expect a proportionate progress and potential in modelling urban flooding within the DCs. Unfortunately, the problem of uncertainty and model sensitivity to external datasets and test locations still prevails [153]. Thus, to improve a wider application of flood modelling procedures which benefits primarily the DCs, the research community should focus attention into calibration through uncertainty and sensitivity analyses. More investigations are needed towards developing bespoke models that are capable of simulating flood inundation hazard without much dependence of distributed topographic and friction datasets.

Declaration of Competing Interest

None.

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