International Journal of Nanoelectronics and Materials
Volume 15 (Special Issue) March 2022 [81-100]

Advance Flood Inundation Model Toward Flood Nowcasting: A Review

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ABSTRACT

Flood nowcasting is a short time prediction (usually less than 3 h) of the spatial and temporal evolution of flood inundation. Typical flood nowcasting consists of several elements, namely data collection system, rainfall forecasting, flood simulation tools, decision support tools and warning process system. Many studies related to the nowcasting system focused on rainfall forecasting but lack of attention towards the flood simulation tool (also known as flood inundation model) in the nowcasting system. This paper reviews the theoretical and functional basis of the recent flood inundation model to meet the need of the flood nowcasting system. The discussion includes factors that contribute to the performance and capabilities of the flood inundation simulation, comparisons of some models, issues in flood inundation modeling related to the flood nowcasting system and future prospects of the flood inundation model.

Keywords: Inundation modelling, flood prediction, hydraulic modelling, hydrodynamic modelling, real-time flood forecasting

1. INTRODUCTION

Flood is known as one of the natural hazards. Continuously increasing urbanization has led to increasing flood risk. Although a good implementation of flood risk management in infrastructure development planning and flood protection methods, complete protection against flood is still impossible. Recently, real-time flood forecasting, also known as flood nowcasting, has been a trend in research study as the alternative method to solve this problem. Flood nowcasting is different than traditional flood forecasting. It is a short time prediction (usually less than 3 h) of the spatial and temporal evolution of flood inundation.

[1] has reviewed flood nowcasting broadly and classified several types of flood nowcasting methods, such as real-time flood forecasting based only on rainfall information and empirical scenarios, real-time flood forecasting based on rainfall information and presimulation, real-time flood forecasting based on real-time data assimilation, and real-time flood forecasting with active feedback to the drainage system operation.

Most implementations of flood nowcasting are in urban areas where flash floods happen, and continuous rainfall in a short time can give a significant problem to community activities. The implementations of flood nowcasting can be seen from the real-time flood warning in Denmark that used high-resolution radar, urban flood warning in France that used weather forecast and real-time hydrological models, flood forecast system in Thailand that used real-time urban

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drainage modeling, and the flash flood forecasting system in Spain that was based on radar and network real-time model.

Commonly used flood nowcasting consists of flood simulation and decision support tools and systems for data collection, rainfall forecasting, and warning process. Each element interacts together continuously. One of the flood nowcasting elements is flood simulation tools, also known as the flood inundation model. It is a computational tool made by the mathematical algorithm to simulate the spatial and temporal evolution of flood inundation by giving the required data.

Flood inundation model can be hydraulic models such as LISFLOOD-FP [2], HEC-RAS [3][4][5][6], MIKE [5-7,8,9], ISIS [5,6], SWMM [10], RMA-2 [11-13], TELEMAC2D [8, 14, 15] or hydrodynamic models such as RRI [16] and FloodMap-HydroInundation2D [17,18] where hydraulic model combines with a hydrological model.

As part of flood prediction system study or implementation, several flood inundation models have been used, such as LISFLOOD-FP [19-21], InfoWorks RS [22], RRI [23], SWMM with 2D diffusive overland flow model [24] and ISIS [25].

In order to establish a fast, stable and accurate flood nowcasting system, it depends not only on rainfall forecasting but also on the simulation of flood inundation model to the spatial and temporal evolution of flood. Previous studies on flood nowcasting only focused on rainfall forecasting, not the flood inundation model. With many flood inundation models available in literature with different capability and concepts, selecting an appropriate flood inundation model for the nowcasting system is important to meet the need for a flood nowcasting system [26]. The selection of flood inundation model not only to choose the fast, stable and accurate model but also to choose a model that can interact or combine well with other elements in the nowcasting system. Limitations and other capabilities of the flood inundation model also need to be well known.

This paper intends to review the currently available flood inundation model. Current issues of the inundation model were assessed and evaluated to sort out flood nowcasting and recommend future flood inundation models for flood nowcasting systems. The aim of this study is to propose a suitable flood inundation model for the nowcasting system.

2. METHODOLOGY

For clarification, several criteria were used in selecting flood inundation to be reviewed. First, the flood inundation model needs to be well known in terms of its use by a practitioner in published paper through a year. Second, three model dimensions were considered, namely 1D, 2D, and coupled 1D-2D. 3D is less suitable due to the complexity and processing time of the model. Moreover, the use of1D, 2D, and coupled 1D-2D models alone is sufficient for flood nowcasting based on the objective of the system. Third, the model needs to consider time steps to see the spatial and temporal of the flood inundation. Forth, the selected flood inundation must be capable of simulating either fluvial and/or pluvial floods without the influence of coastal or tidal effect. The selected flood inundation models are LISFLOOD-FP, HEC-RAS, MIKE, ISIS, SWMM, RRI, RMA-2, TELEMAC-2D, Floodmap-Hydroinundation2D, SOBEK and FLO-2D.

These flood inundation models will be reviewed in terms of the theoretical and functional basis of the model. Some comparisons between models can show the differences and similarities in flood inundation simulation in the nowcasting system. Then, a flood inundation model for future development flood nowcasting system will be proposed. Additional recommendations for prospects in flood inundation models related to flood nowcasting will be specified.

3. FACTORS CONTRIBUTING TO THE FLOOD NOWCASTING SYSTEM

Many potential factors in the flood inundation model influence the flood nowcasting system. Some of the factors can be seen in a review of the flood inundation model done by several researchers. [2] reviewed and compared FLOODSIM, LISFFLOOD-FP, MIKE11, ISIS, ONDA, HEC-RAS, FLUCOMP, RMA-2, TELEMAC-2D, and MIKE21. The authors reviewed and compared flow algorithm, discretization and application by only focusing on the storage cell approach model. Several models without a storage cell approach are still suitable for flood nowcasting modeling.

[27] reviewed and compared the simplified inundation, hydrologic, hydrologic, and hydrodynamic models. The selected models include RFIM, RFSM, FCDC, USISM, GUFIM, CA approach, LISFLOOD-FP, SWMM, and 2D hydrodynamic. The comparison was made on flow algorithm, discretization, application, runoff generation, and model input and output. The authors considered the model with final inundation extent as model output, where for flood nowcasting, it needs to be spatial-temporal evolution of runoff as output. This paper divides the factors into theoretical and functional bases. Detail reviews on the contributing factors are discussed in the next section.

3.1 Theoretical Basis

3.1.1 Discretization Unit

The discretization unit is significant in creating a simulation that can be more realistic. However, increasing the discretization unit will increase the processing time. Thus, a 2D discretization unit made based on a structure grid from DEM sources might be a promising nowcasting system. The accuracy of this method depends on the size of the DEM grid used. High DEM resolution gives a highly realistic physical model. Inundation models like LISFLOOD-FP and RRI, which also use DEM to simplify the discretization unit, will also give more advantages to the nowcasting system by processing the simulation using the coupled 1D-2D dimension. This approach allows the model to be more realistic. Comparison in terms of discretization unit was also made by [28] between RMA-2 and SOBEK.

Based on the discretization unit, most of the 1D models (HEC-RAS, MIKE, and ISIS) used the threat domain as a series of cross-sections perpendicular to the flow direction. The accuracy of the model depends on how much cross-section data is available. This type of model is simple and fast in modeling but limited to the river and floodplain inundation simulation (fluvial flood) only. The SWMM model is a little bit different where this model focuses on the flow line network system. This discretization unit is used to identify inundation in a sewer system. 2D models mostly use structure or unstructured grid, and some model users can choose either one. This discretized unit can be created manually or automatically from the Digital Elevation Map (DEM). For coupled 1D-2D models (HEC-RAS, MIKE and ISIS), a combination of two discretization units from 1D and 2D systems was used. It is different from coupled 1D-2D models like LISFLOOD-FP and RRI. Although both models use a 2D structure grid based on DEM, the model identifies river and process river flow based on the 1D method.

Another significant factor is the numerical scheme method used to solve the flow algorithm in the discretization unit. In literature, most flow inundation models used finite differences, finite elements, finite volumes, Runge-Kutta discontinuous Galerkin and cellular automata (CA) numerical scheme for flow algorithm [29]. The ability of an implicit finite volume algorithm allows larger computational time steps than explicit methods. It has also enhanced the stability and robustness compared to finite difference and finite element scheme. The finite volume scheme can also handle subcritical, supercritical and mixed flow regimes (flow passing through critical depth, for example, hydraulic jump). HEC-RAS, MIKE, and TELEMAC-2D models are capable of using a finite volume scheme. Despite several advantages of using finite volume, the numerical scheme might increase the computational time of the flood inundation model. So far, very little attention has been paid to the role of the numerical scheme method. There is a need to compare all numerical scheme methods to know each scheme's capability and ability in terms of the contribution to the flood nowcasting system.

3.1.2 Runoff Generation Calculation

There are two types of runoff generation calculation. First, the sub-catchment area is determined at an arbitrary point. Runoff from the upstream sub-catchment area is given to the flood routing model as a boundary condition. The model is known as the hydraulic model and normally needs a hydrology model to produce a discharge for the upstream source of flow like LISFLOOD-FP, HEC-RAS, MIKE, ISIS, RMA-2, TELEMAC-2D, SOBEK.

Second, using detailed rainfall distribution to generate runoff such as RRI. The model is known as the hydrodynamic model. This model is good in terms of hydrological representation compared with the hydraulic model. It gives a good potential inundation model for the nowcasting system because it reduces the processing time and element in the nowcasting system by combining hydrology and hydraulic modeling. The capability of the hydrodynamic model was also recognized by [1] and [30].

More attention must be taken when applying the hydraulic model in the flood nowcasting system. One of the potential problems using the hydraulic model is when rainfall distribution of the study area significantly contributes to the source of flood inundation, not only from upstream runoff, which means pluvial flood type happen. Thus, specific attention needs to take into consideration while using this type of model.

Although the hydrodynamic model considered rainfall distribution input data, the hydrology concept inside the hydrodynamic model also needs to be reviewed.

3.1.3 Flow Spreading Algorithm

Flow spreading algorithm can use the Saint Venant equation or simplify it by neglecting different terms of the momentum equation. To understand the various flow spreading algorithms, 1D analysis is used. 1D Saint Venant equations expressed in terms of the section mean velocity, u:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\left(\frac{\partial d}{\partial x} + S_f - S_0\right) = 0 \quad (1)$$

(i) (ii) (iii) (iv) (v)

in which, d = depth of flow; S_f = friction slope; S_0 = bed slope; t = time.

In Equation (1), (i) represent the local inertia (or acceleration) term, (ii) represents the advective inertia term, (iii) represents the pressure differential term, and (iv) and (v) account for the friction and bed slope respectively. After dividing Equation (1) by gravitational acceleration, g, the different types of flood flow model and the terms used to describe them can be written [31]:

$$\frac{1}{g}\frac{\partial u}{\partial t} + \frac{u}{g}\frac{\partial u}{\partial x} + \frac{\partial d}{\partial x} + \left(S_f - S_0\right) = 0 \quad (2)$$

(i) (ii) (iii) (iv) (v)

From Equation 2, the wave models and terms used to describe it are: (1) kinematic wave (iv), (2) diffusion wave (iii) + (iv), (3) steady dynamic wave (ii) + (iii) + (iv), (4) dynamic wave (i) + (ii) + (iii) + (iv), and (5) gravity wave (i) + (ii) + (iii).

The full Saint Venant equation is applicable to the widest range of flow conditions. This equation is also a real advantage to the flood inundation prediction. Using it over complex topography can lead to problems of instability and convergence because of the highly nonlinear, hyperbolic nature of the governing equations [32-33]. From a prediction point of view, the equation is also too computationally intensive or time-consuming to develop. Therefore, practitioners tend to simplify it by neglecting different momentum equation terms whenever justified by the physical conditions.

The analysis made by [34] between full Saint Venant equation, inertia Saint Venant equation and diffusion wave equation showed that diffusion wave equation ease of use, simplicity, stability and small mass errors might be desirable, where the model is applied to cases when it is difficult to check model results, where only diffusive process representation is required and where coarse resolution models are needed.

One of the disadvantages of the simple models is that it is unable to simulate hydraulic jumps and wake zones [34]. The Saint Venant equation was required when subcritical to supercritical transitions in the flow affect wave propagation [34].

Four equations are mostly used in the inundation model, namely Saint Vanent equation, diffusion wave equation, kinematic wave equation and dynamic wave equation. Some models enable to choose between the Saint Venant equation and diffusion wave equation or diffusion wave equation and kinematic wave equation. For the coupled 1D-2D model, some models enable combining different equations and dimensions in one solution or simulation like HEC-RAS enable combining the 1D Saint Venant equation for river flow simulation with 2D diffusion wave for the floodplain.

The variety of algorithm combinations and algorithm options in one model gives advantages in prediction where a wider range of topography can be used and at the same time reduce the computational time for simulation processes.

Although the full Saint Venant equation is the complete set equation suitable for a wide range of the topography, it gives a significant problem in terms of computation processing time. By knowing the topography of the selected area, an appropriate simplification equation can be used to reduce the disadvantages of the full Saint Venant equation. Here, the capabilities of the model like HEC-RAS give an advantage where users can compute using full Saint Venant equation or simplification equation (diffusion wave equation). Table 1 shows a detailed theoretical comparison of representative flood inundation model in specific factors, namely discretization unit, runoff generation calculation and flow spreading algorithm.

3.2 Functional Basis

3.2.1 Input Data

Input data required mostly depends on the types of model, either hydraulic or hydrodynamic. Most hydraulic models need topography data, river inflow condition, river outflow condition, surface roughness, time step, and hydraulic structure details. For the hydrodynamic model, river inflow and outflow conditions were not required but replaced with rainfall intensity distribution data.

3.2.2 Output Data

All inundation models give similar concept or output data in terms of spatial-temporal evolution of runoff except the SWMM model. This is needed in nowcasting to identify flood extent and water level of the flooded area. For the SWMM model, the output shows inundation on the sewer system. It is given by the hydrograph of each surcharge manhole which is point hydrograph [35-36].

3.2.3 Flood Type

Flood type can be classified into two, pluvial flood and fluvial flood. Pluvial flood is a surface water flood and is sometimes known as non-source flooding. According to [37], "Non-source flooding refers to all points where the elevation is below a given water level belongs to the flooded area, equivalent to a large area receiving uniform precipitation in which all low-lying areas are likely flooded." Fluvial flood is a river flood, also known as source flooding. [37] defined fluvial flood as "source flooding, not only considered water level compared to the terrain, but also flow continuity."

Flood type depends on several factors, such as land use, location, and amount of rainfall intensity distribution. In order to select an appropriate inundation model, understanding the environment of the study area is important. The causes for both types of flood occurrences due to some environmental issues are sometimes difficult to identify. When the nowcasting system focuses on the fluvial flood, the system will become less accurate to predict pluvial flood. Similarly, it will be less accurate to predict when fluvial floods happen.

3.2.4 Flood Inundation Study

For clarification, only studies that meet this paper's scope were reviewed and selected. Four categories of resolution area can be seen: catchment area, floodplain area, urban area, and sewer system. For studies using the RRI model, they used catchment area resolution. Most hydraulic models used floodplain area resolution such as HEC-RAS, MIKE, ISIS, RMA-2, TELEMAC-2, and SOBEK. In urban surface area resolution, Floodmap-HydroInundation2D and FLO-2D can simulate. For the urban sewer system, the resolution shows SWMM can simulate.

LISFLOOD-FP already covers almost all size ranges of the fluvial flood, as seen in the flood inundation study. RRI model mostly covers large-scale catchment studies. Other models cover the small to medium size study areas or length of the river.

Hydraulic models such as HEC-RAS and MIKE mainly focus on river and river floodplain inundation processes, while the hydrodynamic model, like the RRI model, focuses on the catchment inundation process. Inundation models like SMMM focus on sewer systems and sometimes combine with other models for surface inundation [35-36]. Thus, it can be seen that each model was mainly developed to simulate the specific types of inundation and environment scopes. Table 2 shows a detailed functional comparison of the representative flood inundation model.

Table 1 Theoretical Comparison of Representative Flood Inundation Model

Name of Model / Model Dimension / Model Type /The Authors	**Discretization Unit**	**Runoff Generation Calculation**	**Flow Spreading Algorithm**		
			Unidentified Flow	**Identified Flow**	
				Channel Routing	**Floodplain/Overland Routing**
LISFLOOD-FP (coupled 1D-2D) Non-commercial model [38]	Raster-based discretisation derived automatically from a DEM grid of uniform square cells. The lateral flow model used storage cell concepts with explicit finite different method for numerical scheme.	Sub-catchment area is determined at arbitrary point. Runoff from sub-catchment area is given to the flood routing model as boundary conditions. External hydrological model needed.	None	Optional either 1D Kinematic wave equation, 1D diffusive wave equation or 1D Sub-grid channel	Optional either 1D on 2D grid routing, 1D on 2D grid diffusive wave equation, 1D on 2D grid simplified shallow water equation (negligible convective acceleration term) or 2D shallow water equation.
HEC-RAS (1D; 2D; coupled 1D-2D) Non-commercial model [3-4]	1D application Treats domain as a series of cross sections perpendicular to the flow direction with implicit finite difference method for numerical scheme. 2D application Unstructured and/or structure grids and can use up to eight sides of elements with finite volume method as numerical scheme. Coupled 1D-2D application Combination of 1D and 2D discretization unit	Sub-catchment area is determined at arbitrary point. Runoff from sub-catchment area is given to the flood routing model as boundary conditions. External hydrological model needed. Common external hydrological model tools used is HEC-HMS.	1D application 1D Saint Venant equations 2D application 2D Saint Venant equation or 2D Diffusion Wave equation Coupled 1D-2D application None	1D application None 2D application None Coupled 1D-2D application 1D Saint Venant equations	1D application None 2D application None Coupled 1D-2D application 2D Saint Venant equation or 2D Diffusion Wave equation
MIKE (1D; 2D; Coupled 1D-2D) Commercial model [39-43]	1D application Treats domain as a series of cross sections perpendicular to the flow direction with implicit finite difference method for numerical scheme 2D application	Sub-catchment area is determined at arbitrary point. Runoff from sub-catchment area is given to the flood routing model as boundary conditions. Commonly used Rainfall-Runoff (RR) model build in MIKE.	1D application Optional either 1D dynamic wave equations, 1D diffusion wave equations or 1D kinematic wave equations.	1D application None 2D application None	1D application None
	Structured grids (finite difference methods) or unstructured grids (finite volume and finite element methods) using a variety of geometries, but typically triangles or quadrilaterals. Coupled 1D-2D application Combination of 1D and 2D discretization unit		2D application 2D Saint Venant equations Coupled 1D-2D application None	Coupled 1D-2D application Optional either 1D dynamic wave equations, 1D diffusion wave equations or 1D kinematic wave equations.	2D application None Coupled 1D-2D application 2D Saint Venant equations
ISIS (1D; 2D; Coupled 1D-2D) Commercial model [5, 12, 44]	1D application Treats domain as a series of cross-sections perpendicular to the flow direction, with FAST (similar to a storage cell concept) as a numerical scheme.	The sub-catchment area is determined at an arbitrary point. Runoff from the sub-catchment area is given to the flood routing model as boundary conditions. External hydrological model.	1D application 1D Saint Venant equation	1D application None	1D application None

Table 1 Continued…

Name of Model / Model Dimension / Model Type /The Authors	Discretization Unit	Runoff Generation Calculation	Flow Spreading Algorithm		
			Unidentified Flow	Identified Flow	
				Channel Routing	Floodplain/Overland Routing
	2D application Rectangular structure grid model with 3 numerical scheme options, namely alternating direction implicit (ADI), Total Variation Diminishing (TVD) or FAST. Coupled 1D-2D application Combination of 1D and 2D discretization unit		2D application 2D Saint Venant equation Coupled 1D-2D application None	2D application None Coupled 1D-2D application 1D Saint Venant equation	2D application None Coupled 1D-2D application 2D Saint Venant equation
SWMM (1D) Non-commercial model [45-47]	Treat domain as a conveyance network of a series of nodes connected by links with an explicit numerical scheme.	Sub-catchment area is determined at an arbitrary point. Runoff from the sub-catchment area is given to the flood routing model as boundary conditions. External hydrological model.	Optional either Kinematic wave equation and dynamic wave	None	None
RRI (coupled 1D-2D) Non-commercial model [48]	Uniform rectangular structure grid model. Grid size depends on DEM input data resolution. The lateral flow calculation based on storage cell based on the Runge-Kutta method as numerical scheme.	Use details rainfall to generate runoff. Each grid would be calculated runoff. Calculated runoff flows to the rivers as surface runoff, lateral subsurface runoff, and vertical infiltration runoff, according to the water level gradient. - Distributed Hydrograph Model	None	1D diffusive wave model with kinematic wave is also selectable	2D diffusive wave model with kinematic wave is also selectable
RMA-2 (2D) Commercial model [11-13, 49]	Unstructured grids using triangles or quadrilaterals used the finite element method as a numerical scheme.	Sub-catchment area is determined at an arbitrary point. Runoff from the sub-catchment area is given to the flood routing model as boundary conditions. External hydrological model needed. - VSAS3 [11]	None	2D Saint Venant equations	2D Saint Venant equations
TELEMAC-2D (2D) Non-commercial model [50]	Unstructured grids using triangle elements with option finite element method or finite volume method as numerical scheme.	Sub-catchment area is determined at an arbitrary point. Runoff from the sub-catchment area is given to the flood routing model as boundary conditions. External hydrological model needed.	Full solution of the 2D Saint Venant equations	None	None

Table 1 Continued…

Name of Model / Model Dimension / Model Type /The Authors	Discretization Unit	Runoff Generation Calculation	Flow Spreading Algorithm		
			Unidentified Flow	Identified Flow	
				Channel Routing	Floodplain/Overland Routing
SOBEK (1D; 2D; coupled 1D-2D) Commercial model [51]	1D application Treats domain as a series of cross-sections perpendicular to the flow direction with Delft-scheme method as numerical scheme. 2D application The rectangular staggered structure grid model uses a finite difference method called Delft-scheme as a numerical scheme. Coupled 1D-2D application Combination of 1D and 2D discretization unit	Sub-catchment area is determined at an arbitrary point. Runoff from the sub-catchment areas is given to the flood routing model as boundary conditions. External hydrological model needed. Common external hydrological model tools used is Rainfall-Runoff modules in SOBEK.	1D application 1D Saint Venant equations 2D application 2D Saint Venant equations Coupled 1D-2D application None	1D application None 2D application None Coupled 1D-2D application 1D Saint Venant equations	1D application None 2D application None Coupled 1D-2D application 2D Saint Venant equations
FLO-2D (coupled 1D-2D) Commercial model [52]	Uniform, rectangular structure grid model with explicit finite difference method as numerical scheme.	Three option: 1) Using detailed rainfall to generate runoff. Each grid would be calculated runoff as surface runoff. 2) Sub-catchment area is determined at an arbitrary point. Runoff from the sub-catchment area is given to the flood routing model as boundary conditions.FLO-2D can use to generate runoff/flood hydrograph or using an external hydrological model. 3) Implement options (1) and (2).	1D on 2D grid dynamic wave equation	1D dynamic wave equation	1D on 2D grid dynamic wave equation

The next section presents some comparisons of flood inundation models to show the difference and similarities between flood inundation models.

4. COMPARISON OF FLOOD INUNDATION MODEL

4.1 Comparison Between HEC-RAS and RRI Model

HEC-RAS model is a well-known and widely used 2D simulation developed by the US Army Corps of Engineers. This model is capable of performing steady and unsteady flow hydraulic, sediment transport computation and water temperature modeling. Many studies have been done using 1D model, such as unsteady flow and sediment modeling [53], flood analysis [54-56] and river water surface profile simulation [57]. Recently, a new version of HEC-RAS, namely HEC-RAS 5.0, enhanced the previous 1D version simulation with 2D and coupled 1D-2D system, giving the new capability of the HEC-RAS.

The RRI model developed by [48] is capable of simulating rainfall-runoff and flood inundation simultaneously. The model deals with slopes and rives channels separately. The river channel is simulated on a 1D basis, while lateral flows are simulated on a 2D basis. This allows the RRI model to simulate the flood inundation in a coupled 1D-2D platform. The RRI model was mainly developed to simulate the flood inundation model on a catchment basis. In terms of cost, HEC-RAS and RRI were non-commercial models, which means both models are more economical. Despite being non-commercial, both models show significant capability for flood inundation simulation.

Regarding hydrological cycle consideration, the RRI is more capable because it can simulate rainfall, runoff and inundation. In contrast, HEC-RAS can only simulate runoff to inundation. Thus, HEC-RAS required an additional hydrological tool (commonly HEC-RAS model) to simulate rainfall-runoff. In the nowcasting system, an additional tool might increase uncertainty and computation time.

In terms of accuracy, HEC-RAS is more accurate than the RRI model based on the theoretical basis of the model. Although both models can perform coupled 1D-2D model that is more accurate compared to single 1D and 2D, the discretization concept seems different. In a 2D discretization unit, HEC-RAS can perform an unstructured or structured grid with up to eight elements while the RRI model only performs based on rectangular structure grid and depending on the digital elevation map grid. Thus, the variety of the discretization HEC-RAS model increases the physical realistic. Besides, HEC-RAS performs the simulation using the full Saint Venant equation with an optional algorithm by simplifying the Saint Venant equation, namely the diffusion wave equation. Compared to the RRI model, which used simplification algorithm either diffusion wave equation or kinematic wave equation. For functional basis, HEC-RAS output results are smoother than the RRI, following rectangular grid shape. Thus, logically less accurate for the flood extent. HEC-RAS is also capable of considering hydraulic structures such as bridges and culverts. This additional capability gives more accuracy to the model.

In terms of computation time, the RRI model has a shorter computation time than the HEC-RAS model based on the theoretical and functional basis of the model. Firstly, as a hydrodynamic model, the RRI model does not need an additional hydrological model for runoff generation calculation. Secondly, an increase in the accuracy of the HEC-RAS increases the computational time of the model due to the preparation of the meshing process. To give high accuracy, the unstructured grid developed manually is required. Thus, give more time for the preparation. Besides, using the full Saint Venant equation gives more variables than the simplified algorithm. Thus, logically it gives more computation time than the simplified algorithm.

Table 2 Function Comparison of Representative Flood Inundation Model

Name of Model / The Authors / Model Dimension / Model Type	Model Input	Model Output	Flood Type in the Application	Flood Inundation Study
LISFLOOD-FP (coupled 1D-2D) Non-commercial model [38]	Topography data; River inflow condition; River outflow condition; Surface roughness; Time step; Hydraulic structure details	Spatial-temporal evolution of runoff	Fluvial flood	60 km River Severn, UK [58-60] ~16 km River Severn West-Central England [61] 35 km River Meuse [61] ~0.5km^2 Urban Greenfields area of Glasgow [62-66] 3.7km x 2 km, Tewkesbury Town [67] 4 km Upper River Thames, UK [68] 14.75 km^{2}City of Carlisle [20][69] 800 km River Niger in Mali [70] ~170,000 km^{2}Lower Zambezi River in southeast Africa [71] 7 km Rafina River, Greece [72] 40 km Peneios River, Greece [72]
HEC-RAS (1D; 2D; coupled 1D-2D) Non-commercial model [3-4]	<u>1D application</u> Topography; River inflow condition; River outflow condition; Surface roughness; Time step; Hydraulic structure details; <u>2D and coupled 1D-2D application</u> Topography; River inflow condition; River outflow condition; Surface roughness; Rainfall intensity distribution; Time step; Hydraulic structure details;	Spatial-temporal evolution of runoff	Fluvial flood	<u>1D application</u> Along River Severn [73] River Severn, UK [59] San Antonio and Medina Rivers and the Salado, Cibolo, and Leon Creeks [74] 7 km Rafina River, Greece [72] 40 km Peneios River, Greece [72] <u>2D and coupled 1D and 2D application</u> None
MIKE (1D; 2D; Coupled 1D-2D) Commercial model [39-43]	<u>1D application</u> Topography; River inflow condition; River outflow condition; Surface roughness; Time step; Hydraulic structure details <u>2D and coupled 1D-2D application</u> Topography; River inflow condition; River outflow condition; Surface roughness; Rainfall intensity distribution; Time step; Hydraulic structure details	Spatial-temporal evolution of runoff	Fluvial flood	<u>1D application</u> 6 km Sungai Kayu Ara, Malaysia [75] ~500 km Scheldt River, Belgium [76] 2.2 km Xerias River, Greece [77] <u>2D application</u> 2.2 km Xerias River, Greece [77] <u>Coupled model (1D-2D)</u> 2.2 km Xerias River, Greece [77]

Table 2 Continued…

Name of Model / The Authors / Model Dimension / Model Type	Model Input	Model Output	Flood Type in the Application	Flood Inundation Study
ISIS (1D; 2D; Coupled 1D-2D) Commercial model [5, 12, 44]	Topography; River inflow condition; River outflow condition; Surface roughness; Time step; Hydraulic structure details	Spatial-temporal evolution of runoff	Fluvial flood	<u>1D application</u> 21 km River Crouch, UK [25] <u>2D application</u> ~3 km^2 area close to River Alde [78] <u>Coupled 1D-2D application</u>
SWMM (1D) Non-commercial model [45-47]	Topography data with detailed sewer system; Inflow condition; Surface roughness; Time step; Hydraulic structure details;	Flow Hydrograph;	Pluvial flood	2.77 km^{2}Sanxia district, Taiwan [35] Downtown Taipei, Taiwan [36]
RRI (coupled 1D-2D) Non-commercial model [48]	Topography; River inflow condition (optional); Surface roughness; Rainfall intensity distribution; Time step;	Spatial-temporal evolution of runoff. - All results showed based on grid shape, including flood extent and river sinuosity.	Fluvial flood	1,800 km^{2}Upper Citarum Basin, Indonesia [79] 92 605 km^{2}Kabul River basin [16] 160 000 km^{2}Chao Phraya River Basin [80,81] 23,616 km^{2}Yom River Basin [23]
RMA-2 (2D) Commercial model [11-13]	Topography; River inflow condition; River outflow condition; Surface roughness; Time step; Hydraulic structure details	Spatial-temporal evolution of runoff	Fluvial flood	14 km River Culm in Devon, UK [8][26] 11 km River Culm in Devon, UK [82] 24 km River Fulda in West Germany [83] Lima river [28]
TELEMAC-2D (2D) Non-commercial model [50]	Topography; River inflow condition; River outflow condition; Surface roughness; Time step; Hydraulic structure details	Spatial-temporal evolution of runoff	Fluvial flood	14 km River Culm in Devon [8] 60km River Severn, UK [59] 4 km Upper River Thames, UK [68]

Table 2 Continued…

Name of Model / The Authors / Model Dimension / Model Type	Model Input	Model Output	Flood Type in the Application	Flood Inundation Study
SOBEK (1D; 2D; coupled 1D-2D) Commercial [51]	Topography; River inflow condition; River outflow condition; Surface roughness; Time step; Hydraulic structure details	Spatial-temporal evolution of runoff	Fluvial flood	<u>1D application</u> <u>2D application</u> Lima river [28] <u>Coupled 1D-2D application</u>
FLO-2D (coupled 1D-2D) Commercial [52]	Topography; River inflow condition; River outflow condition; Surface roughness; Rainfall intensity distribution; Time step; Hydraulic structure details	Spatial-temporal evolution of runoff	Pluvial and Fluvial flood	150 km^2 Hat Yai City, Thailand [84]

HEC-RAS and RRI give a different resolution scope and concepts in terms of model resolution. HEC-RAS, most of the time, focuses on a single river path flood inundation process while the RRI model focuses on a single catchment flood inundation process. Thus, HEC-RAS is basically a micro model compared to the RRI model, which is more on the macro model. The selection of either HEC-RAS or RRI model depends on the area's flood history. For large-scale flood inundation with several flood sources, the RRI model is more suitable while for small-scale flood inundation involving the street level and resolution needed, then a detailed model like HEC-RAS is required.

4.2 Comparison Between HEC-RAS and MIKE Model

MIKE model was developed by the Danish Hydraulic Institute. There are 3 different series of MIKE models capable of simulating flood inundation at different dimension types: MIKE 11, MIKE 21 and MIKE FLOOD. MIKE 11 is a 1D hydraulic model mainly designed to execute a detailed description of the flow over hydraulic model (e.g. culverts, weir, etc.). This 1D model has been used extensively in many studies (e.g. [85, 86]). MIKE 21 is a 2D model that can use different terrain set-ups: rectangular grid (MIKE 21 HD) and flexible mesh element (MIKE 21 HD FM). This 2D model is designed to comprehensively describe the flow over the hydraulic structure with 2D bases. MIKE 21 model has been widely used for flood-prone areas modeling and mapping (e.g. [87-89]). MIKE FLOOD is the coupling platform for the combination of MIKE 11 and MIKE 21. Numerous studies have demonstrated this hydraulic coupling model, such as [90] and [91].

In terms of cost, HEC-RAS is a non-commercial model that makes the model more economical than MIKE, a commercial model.

In terms of hydrological cycle consideration, both models used similar concepts that can only simulate runoff to inundation (hydraulic model). To perform a rainfall runoff simulation, an additional hydrological tool is needed. Commonly, HEC-RAS is used with HEC-HMS as a hydrological tool, developed by the US Army Corps of Engineers. MIKE is usually used with the Rainfall-Runoff module that Danish Hydraulic Institute also developed.

In terms of accuracy, both models are slightly similar due to the concept of both models being slightly similar either 1D, 2D and coupled 1D-2D. Additional studies are needed to clarify the accuracy between both models.

In terms of computational time, reviewing the theoretical basis of the model is also hard to compare due to the similarity of the basic concept of both models. However, small differences can be seen in terms of the numerical scheme used for 2D application and 2D in the coupled 1D-2D application, where HEC-RAS used implicit finite volume method either structured or unstructured grids while MIKE uses finite-difference for structure grid finite volume and finite element for unstructured grids. This numerical scheme might give a difference in computation time. Besides, it is also different options in the spreading flow algorithm used. MIKE gives options of flow algorithm in 1D application while HEC-RAS gives options of flow algorithm in 2D application.

In terms of model resolution, both hydraulic models focus on a single river path flood inundation process. Both models can simulate small-scale flood inundation involved at the street level resolution needed and consider hydraulic structure. Thus, the resolution of both models is similar.

5. ISSUES FLOOD INUNDATION MODELLING

Selecting an appropriate inundation model in the nowcasting system depended not only on the model itself but also on how it can cooperate or link between other elements in the nowcasting system. These issues will be underlined and discussed in this section.

5.1 Level of Simplification and/or Complexity of the Model

Inundation modeling in flood nowcasting seems to face a problem on how simple and complex the model is required or its suitability in flood nowcasting system. Increasing the simplification scope shows less accuracy of the modeling while increasing the complexity will increase the cost and processing time and may require high quality of data. Most researchers suggested that it depends on the purpose of the modeling [15, 92]. Here, inundation modeling used as part of the flood nowcasting is well known to predict flood in a short period to be used in flood risk management. Thus, the inundation modeling needs more simplification than complex, depending on the resolution of the result needed and the land use of the topography. A standard level of simplification must be proposed with a specific percent of accuracy in modeling. Future work should be directed towards a standard level of simplification balanced with the complexity of the modeling.

5.2 Link with Input Data

Linking between continuous input data like rainfall distribution and discharge hydrograph to the inundation model in the nowcasting system is another issue that must be determined. Fewer studies have been made to identify the best solution to these issues. Most studies focus on the proposed complete nowcasting system without critically analyzing these issues. There are different ways that each inundation model reads the input data. [24] approved this, who proposed a data converter element inside the nowcasting process before the input data used in the inundation model. Easier inundation model reading the input data gives a significant advantage to the nowcasting system.

5.3 Updating Input Data, Validation and Calibration Schedule

By looking into a continuous nowcasting system, standard inundation modeling processes must also be continuous. This includes updating input data, validating inundation results, and model calibration. Table 3 shows the preliminary suggestion schedule for updating input data. Understanding the site environment is important in deciding the schedule of updating input data.

Table 3 Suggestion to Schedule Updating Input Data

Data Type	Topography Data	Surface Roughness	River Inflow Condition	Rainfall Distribution	River Outflow Condition
Update period	Rural: > 5 year Urban: < 5year	Rural: > 5 year Urban: < 5 year	Continues	Continues	Continues

* River inflow and river outflow condition for hydraulic model, rainfall distribution for hydrodynamic model

In terms of validation and calibration, the accuracy of the model in nowcasting will be sustainable if the model rapidly validates and calibrates, especially when major changes or major rainfall occurs. An additional system or tool for the inundation model in nowcasting is needed for this purpose. The online system also will be an added value. Two methods for calibrating and validating are normally used: flood extent data and flow depth or/and discharge data obtained from gauging stations. To continuously use flood extent data for calibrating and validating might be difficult to use due to collecting the flood extent data. Consequently, flow depth or/and discharge data might suit the nowcasting system in this scope.

6. FUTURE PROSPECT AND CONCLUSION

Flood nowcasting systems have been a trend recently as the alternative solution for implementing flood risk. Most flood nowcasting system studies focus on rainfall forecasting elements but lack attention to the flood inundation model. Therefore, this review assessed and evaluated the widely used flood inundation model for flood nowcasting systems.

Modeling factors contributing to the flood nowcasting system were discussed theoretically and functionally. Fully development of a flood nowcasting system that supports prediction from catchment resolution, river floodplain, and piping system is possible by combining several flood inundation models, namely RRI, HEC-RAS and SWMM model. These combinations give a high understanding of the source of the flood and enhance the accuracy of prediction. However, the computation time of this implementation gives the potential problem to the flood nowcasting system.

Comparison between several models on advantages and disadvantages of flood nowcasting were discussed. Some models give different capabilities and some models give almost similar capabilities. There is a need to understand the model's theoretical and functional, especially in terms of cost, hydrological cycle, accuracy, computation time, and model resolution, to implement in flood nowcasting system. HEC-RAS model shows a good potential model for flood nowcasting systems with a specific terrain resolution. This model is more economical than the commercial model, with almost similar concepts to the commercial model like MIKE. Therefore, it is suggested to implement the HEC-RAS model as a flood inundation model for the flood nowcasting system.

The discussion on issues in the flood inundation model shows that there is a need to understand the performance and stability of the inundation model using continuous input data.

ACKNOWLEDGEMENTS

This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through Tier 1 (Vot Q033).

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