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One- and Two-Dimensional Hydrological Modelling and Their Uncertainties

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Abstract

Earth processes, which occur in land, air and ocean in different environment and at different scales, are very complex. Flooding is also a part of the complex processes, which need to be assessed accurately to know the accurate spatial and temporal changes of flooding and their causes. Hydrological modelling has been used by several researchers in river and floodplain modelling for flood analysis. In this chapter, factors affecting flash flood, possible options of basic input parameters in one- and two-dimensional hydrological models in data sparse environment, some case studies and uncertainty in hydrological modelling were discussed. This discussion will help the readers to understand the flooding factors, selection of input parameters in data sparse environment, a brief insight of one- and two-dimensional hydrological models and uncertainties in their input and model parameters and model structures.

Keywords: flooding, floodplain, modelling, river, uncertainties

1. Introduction

Natural hazards are inevitable, unfortunate events resulting from combination of natural, geological and anthropogenic disturbances. Flooding is one of the main natural hazards and occurs frequently all over the world [1], especially in Asia and Africa than other countries. Every year, flooding incurs loss of life, economy, environment and agriculture. Economic loss includes damage to businesses, residential properties, roads, bridges, buildings and automobiles. As an example, environmental damage includes contamination of water supplies and

destruction to natural habitats by chemical waste and oil spills from vehicles and industrial facilities. According to the United Nation's report [2], floods accounted for 47% of all weather-related disasters since 1995, affecting 2.3 billion people, killing 1.57 lakhs and incurring damages of about US\$19.3 billion and US\$0.83 billion in Asia and Africa, respectively [3].

Flooding is mainly caused as a result of increased settlement along levees, unexpected high rainfall, deforestation, sediment deposition and river channel changes [4–7]. Due to heavy rainfall in a short period of time, rivers are unable to transport the increased volume of water and other materials along its course that results in over-bank flow causing inundation of neighbouring lands. Once the river water has overflowed or breached the levees, water races through the almost level flood plain submerging the cultivated fields and villages along its way causing enormous damage to lives and properties. In-depth exploration into the causes and effects of flooding would lead to improved flood risk monitoring, prediction, mitigation and relief operations. However, poor disaster management practices, limited financial resources and high population pressure are some common characteristics of less developed countries such as Ethiopia, which affects the monitoring, mitigation and relief operations [8].

Hydrological model, a simplified and conceptual representation of complex hydrological processes, provides spatial and temporal changes over large areas and simplifies the complex reality. It is very important to find accurate causes and effects and to understand the behaviour of flooding according to their specific locations. The complex processes of river and floodplain due to combination of natural and anthropogenic activities have been assessed by several researchers [9, 10]. However, hydrological modelling has some uncertainties either in input or model parameter, which affects accuracy and efficiency of a model [11, 12]. The poor spatial distribution of basic input and model parameters data in hydrological modelling such as precipitation, evapotranspiration, infiltration and runoff can affect the model accuracy. For example, in complex topography, precipitation has uncertainty in its spatial distribution due to uplifting air masses by the wind. Some studies [13, 14] considered precipitation's spatial discontinuity and used different occurrence/non-occurrence estimation approach to improve the spatial distribution of precipitation. The spatial distribution of input and model parameters also affects the accuracy of river's geometry such as selection of their spacing [15] and channel shape [16].

With the advancement of computational technology, many one-dimensional (1D) and two-dimensional (2D) hydrological models have been developed for both river and floodplain modelling to analyse the behaviour of flooding and to identify the causes and effects of flooding. Several researchers used 1D and 2D models for floodplain modelling [17] and for river modelling [18]. The use of mixed approach of 1D and 2D numerical models increases the quality of results [17] and also saves time and computer memory, which can be limiting factors for the application of 2D models [19]. Bladé et al. [19] studied the conservation of mass and momentum by coupling of 1D and 2D models for river channels and floodplain, respectively. However, results of these models also affected by the complexity and quality of topographic and input data [20, 21].

In this chapter, first, the role of factors affecting flash flood and their use in hydrological modelling will be discussed. Secondly, in data sparse environment, the possible options for basic

input variables for 1D and 2D modelling techniques would be considered. Finally, some case studies based on different 1D and 2D modelling techniques and uncertainties of hydrological modelling will be discussed in brief.

2. Factors affecting flash flood

Precipitation is the most important factor in the occurrence of flash flood, but many other contributing factors such as natural factors such as catchment characteristics, soil type and land use cover or anthropogenic activities at the river and floodplain also increase the flood frequency. Therefore, in this section, the role of these factors and their application in hydrological modelling will be discussed.

2.1. Precipitation

The dynamic behaviour and spatial distribution of precipitation due to climate changes is a major factor of concern. In general, higher precipitation can result in more runoff but the surface condition sometimes will be of greater importance. In hydrological modelling, spatial distribution of precipitation without any discontinuity should be considered in complex topography. Castro et al. [14] studied the effect of precipitation discontinuity in complex topography where orographic and meteorological parameters are effecting the spatial distribution of precipitation. Therefore, seasonal shifting of precipitation, extreme precipitation, orographic effect and behaviour of meteorological parameters such as wind characteristics, temperature and relative humidity are very important to understand the behaviour of precipitation in any region to get accurate results in hydrological modelling.

2.2. Catchment characteristics

A drainage basin is an area having a common outlet for its surface runoff. When rain falls on a drainage basin, the movement of water towards common outlet depends on the size and shape of the area. The size of the contributing area of precipitation in a basin has a direct influence on the total volume of runoff that drains from that basin. Runoff starting from most upstream point of the larger basin will take longer to reach the basin outlet than runoff travelling from the farthest point in the smaller basin, since it needs to travel a longer distance. If the basin is circular in shape, the precipitation will enter the river at roughly the same time because all points in the basin are equidistant from one another and vice versa (**Figure 1**). This will produce a high peak discharge and can lead to flash floods. Basin shape also has an influence on magnitude and timing of the peak flow at the basin outlet. **Figure 2** shows two basins of equal area with different size in which runoff is more likely to arrive at same time to the outlet in small size.

Stream density is another important characteristic of a drainage basin which is the length of all channels within the basin divided by the area of the basin. A drainage basin with a large number of tributaries has a higher stream density than a basin with very few tributary streams. Higher stream density allows the terrain to drain more runoff and vice versa. Moreover, slope

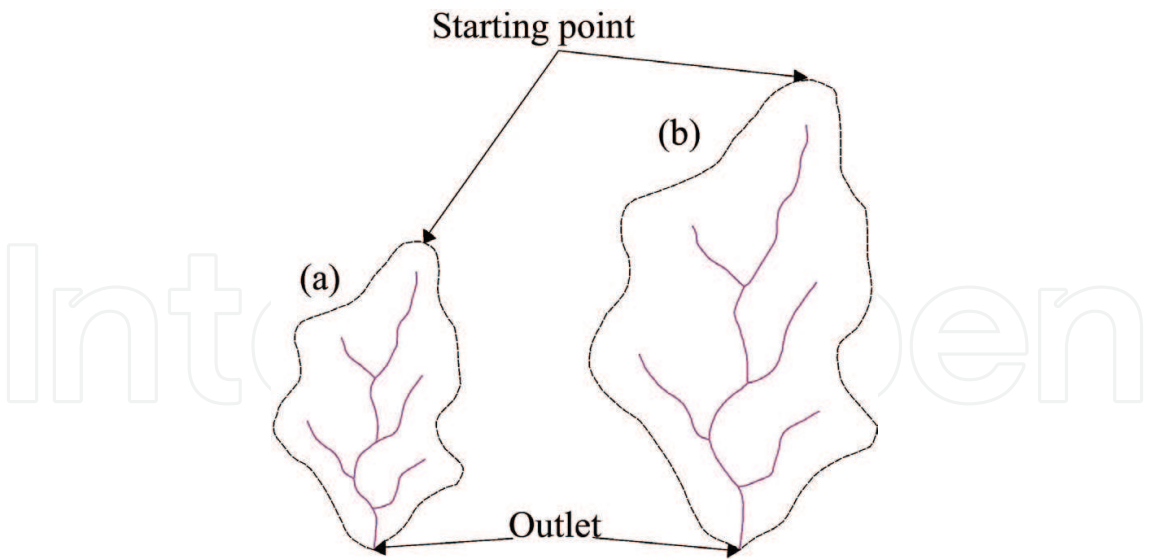


Figure 1. In basin (a), time taken from starting point to the outlet is less as compared to basin (b).

maintains moisture, which increases river’s discharge and triggers flash flood. The above discussions indicates that the basins of the study area should be prioritized on the basis of flood risk and then hydrological modelling has to be carried out in prioritized basins, which will save simulation time and give better results.

2.3. Soil characteristics

Precipitated water first encounters intercepting surfaces such as foliage and man-made structures, then infiltration starts when surface water interacts with soil or bed rock. It first restores the soil moisture deficiency and then percolates downward by the force of gravity and reaches the water

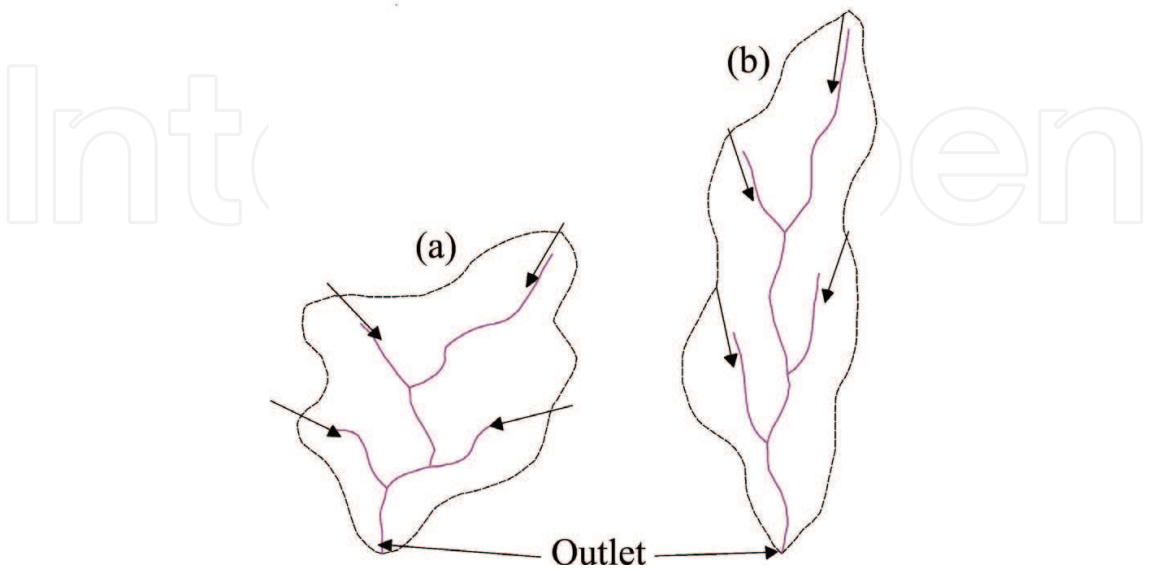


Figure 2. In (a) basin, water is more likely to come at same time than the basin (b).

table [22]. During this process, soil properties and bed rock properties play an important role in the movement of water. Soil texture refers to the relative proportion of sand, silt and clay-sized particles, which controls the infiltration capacity of the basin. Clay and silt soils have the ability to retain high soil moisture while sandy soil ability to retain soil moisture is poor. De Lannoy et al. [23] explained in detail the control of soil properties on the spatial-temporal variability of infiltration and soil moisture processes, while Ref. [24] explained the influence of land use on soil moisture. Apart from soil properties, decomposing plant material on the surface also affects infiltration and runoff considerably. Litter (fresh leaves) and duff (fermented humus) are the two layers on the forest floor [25]. These two layers, especially the duff layer, aids in water repellence and affects the rate of infiltration [26]. **Table 1** shows different hydrological properties for different soil material. These properties should be included in hydrological modelling for accurate results.

2.4. Land use and land cover

Land cover and land use are essential influences on runoff. If a basin has very dense vegetation cover, the vegetation will intercept precipitation and store it, reducing the volume of

Classification	Hydraulic conductivity (in/h)	Porosity	Soil suction	Volumetric moisture deficiency	
				Dry (% diff)	Normal (% diff)
Sand and loamy sand	2.41–8.27	0.437	1.9–2.4	35	30
Sandy loam	1.02	0.437	4.3	35	25
Loam	0.52	0.463	3.5	35	25
Silty loam	0.27	0.501	6.6	40	25
Silt	–	–	7.5	35	15
Sandy clay loam	0.17	0.398	8.6	25	15
Clay loam	0.09	0.464	8.2	25	15
Silty clay loam	0.06	0.471	10.8	30	15
Sandy clay	0.05	0.430	9.4	20	10
Silty clay	0.04	0.479	11.5	20	10
Clay	0.02	0.475	12.5	15	5
Very slow	<0.06 ³				
Slow	0.06–0.20 ³				
Moderately slow	0.20–0.63 ³				
Moderate	0.63–2.0 ³				
Rapid	2.0–6.3 ³				
Very rapid	>6.3 ³				

Table 1. Soil properties that affect infiltration [27].

water entering a river. It also helps in binding the soil. In vegetation-sparse basin, the soil is highly susceptible to mass wasting which can cause huge volumes of sediment deposition on the riverbed which affect hydraulic geometry of a river. The hydraulic geometry refers to the interrelationship between water and sediment discharge, stream width, depth, velocity and river platform [28]. In channel, vegetation slows the velocity of the water flowing in it. The slower the water moves, the higher the water level, and the greater extent to which the floodplain surrounding the river will be inundated. This, however, can reduce downstream flood levels and flows. Vegetation also supports river banks in decreasing erosion and increasing the deposition of sediment. Urbanisation near the river or in floodplain also enhances the flooding frequency by reducing infiltration and increasing surface runoff into a river. Urbanisation generally involves the laying down of tarmac and concrete, impermeable substances that will increase surface runoff into the river and therefore increase the river’s discharge.

In hydrological modelling, man-made structure along the river such as bridges, culverts, embankments, spillways and weirs should be included which gives accurate results for runoff. The runoff coefficient (C) is a dimensionless coefficient in hydrological modelling which is related to the amount of runoff to the amount of precipitation received. It has a larger value for areas with low infiltration and high runoff and lower for permeable, well-vegetated areas. A high C value may indicate flash flooding areas during storms as water moves fast overland on its way to a river channel or a valley floor (**Table 2**).

Area description	C	Area description	C
<i>Business:</i>		<i>Agricultural land:</i>	
Downtown areas	0.70–0.95	<i>Bare packed soil</i>	
Neighbourhood areas	0.50–0.70	Smooth	0.30–0.60
<i>Residential:</i>		Rough	0.20–0.50
Single-family areas	0.30–0.50	<i>Cultivated rows</i>	
Multi-units, detached	0.40–0.60	Heavy soil, no crop	0.30–0.60
Multi-units, attached	0.60–0.75	Heavy soil, with crop	0.20–0.50
Suburban	0.25–0.40	Sandy soil, no crop	0.20–0.40
Apartment	0.50–0.70	Sandy soil, with crop	0.10–0.25
<i>Industrial:</i>		<i>Pasture</i>	
Light areas	0.50–0.80	Heavy soil	0.15–0.45
Heavy areas	0.60–0.90	Sandy soil	0.05–0.25
Parks, cemeteries	0.10–0.25		
Playgrounds	0.20–0.35	Woodlands	0.05–0.25
Railroad yard areas	0.20–0.40	<i>Streets:</i>	
<i>Lawns:</i>		Asphaltic	0.70–0.95
Sandy soil, flat, 2%	0.05–0.10	Concrete	0.80–0.95
Sandy soil, avg., 2-7%	0.10–0.15	Brick	0.70–0.85

Area description	C	Area description	C
Sandy soil, steep, 7%	0.15–0.20	Unimproved areas	0.10–0.30
Heavy soil, flat, 2%	0.13–0.17	Drives and walks	0.75–0.85
Heavy soil, avg., 2–7%	0.18–0.22	Roofs	0.75–0.95
Heavy soil, steep, 7%	0.25–0.35		

Table 2. Runoff coefficient (C) values [29, 30].

The roughness coefficient is also an important factor in terms of energy loss in both river and floodplain flowing water. The Manning's equation is a well-known equation used by almost all hydrological models to calculate channel roughness, which is given by:

$$Q = \frac{c}{n} AR^{\frac{2}{3}} S^{\frac{1}{2}} \quad (1)$$

where c is the constant, Q is the flow (length³/time), A is the cross-sectional area (length²), R is the hydraulic radius (length) = A/P , P is the wetted perimeter (length), S is the slope (length/length) and n is Manning's roughness coefficient. The selection of Manning's n values is important for accurate results because of its high variability and dependence on the number of factors such as surface roughness, vegetation, channel irregularities, channel alignment, scour and discharge, seasonal changes, temperature and suspended material and bedload [31]. **Table 3** shows some basic natural and man-made channel and floodplain conditions with their n values which can be used in hydrological modelling.

Type of channel and description	Range
<i>A. Natural streams</i>	
1. Main channels	
a. Clean, straight, full, no rifts or deep pools	0.025–0.033
b. Clean, winding, some pools and shoals	0.033–0.060
c. Sluggish reaches, weedy, deep pools	0.050–0.080
d. Very weedy reaches, deep pools, or floodways with heavy stands of timber and brush	0.070–0.150
2. Floodplain	
a. Pasture no brush	0.025–0.035
b. Cultivated areas	0.020–0.050
c. Brush	0.035–0.160
d. Trees	0.030–0.160
3. Mountain streams, no vegetation in channel, banks usually steep, with trees and brush on banks submerged	
a. Bottom: gravel, cobbles and few boulders	0.030–0.050
b. Bottom: cobbles with large boulders	0.040–0.070

Type of channel and description	Range
<i>B. Lined or built-up channels</i>	
1. Concrete	0.011–0.025
2. Concrete bottom float finished with different types of sides	0.015–0.035
3. Gravel bottom with different types of sides	0.017–0.036
4. Brick	0.011–0.018
5. Metal	0.011–0.030
6. Asphalt	0.013–0.016
7. Vegetal lining	0.030–0.500
<i>C. Excavated or dredged channels</i>	
1. Earth, straight and uniform	0.016–0.033
2. Earth, winding and sluggish	0.023–0.050
3. Dragline-excavated or dredged	0.025–0.060
4. Rock cuts	0.025–0.050
5. Channels not maintained, weeds and brush	0.040–0.140

Table 3. Manning’s values for different types of channels and floodplains [31].

3. Basic input variables in data sparse environment

In order to achieve accurate flow magnitudes and water levels in 1D and 2D hydrological models, it is needed to use parameters that accurately describe the channel and flood plain geometries [31]. Digital elevation model (DEM) is an input in any hydrological modelling and its resolution significantly affects the accuracy of results. Although high resolution DEM such as airborne LIDAR (light imaging, detection, and ranging) bathymetry (ALB) technology (up to 2.5 m resolution topographical data) is available, the freely available space-borne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) of 30 m resolution and Shuttle Radar Topographic Mission Digital Elevation Model (SRTM DEM) of 90 m resolution can also be used for channel and floodplain geometries. However, ASTER GDEM and SRTM DEM has some limitations such as low penetrating power into a water column in dark or dirty water (**Figure 3**) but it can be enhanced by geographic information system (GIS) by selecting different river cross-section shape.

Several studies have been done for the selection of cross-section shape such as the trapezoid and rectangular (horizontal bottom), semicircle, parabolic, catenary, semi-cubic parabolic, egg and circular sections (curved bottom). These are generally used in different situations such as the hydraulic, economical, hydrogeological and seepage situations [16]. Curved channel, especially the parabolic shape, has the advantages such as slope stability and lacking of sharp edges [32]. Vatankhah [33] mentioned that the best hydraulic sections are those which have the least wetted perimeter for a given cross-sectional area and have the maximum hydraulic

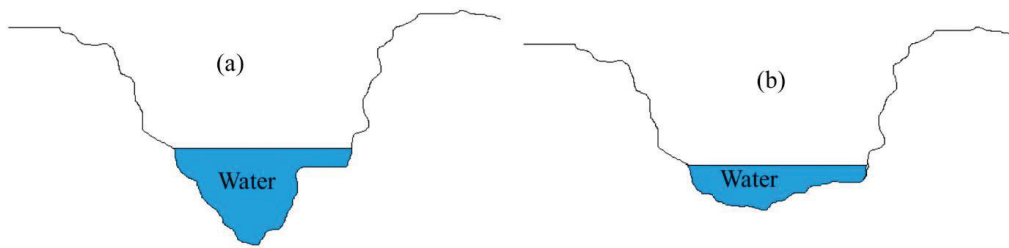


Figure 3. Two river cross sections. Cross section (a) is derived from LIDAR-based DEM while (b) is derived from ASTER GDEM.

radius. As far as channel cross-section spacing is concerned, Ref. [34] presented several guidelines for the choice of cross section and distance between them on the basis of river geometry and flows. Ref. [15] investigated the guidelines and their results confirmed the validity of these rules on the optimal spacing between cross sections. They also mentioned different equations for cross-section spacing based on different situations.

Land use and land cover are also an important input parameter in hydrological modelling because they affect the runoff frequency. The user has to assign values for different land cover classes as given in **Tables 1** and **2**. In high-resolution data sparse environment such as SPOT 5 (2.5 m resolution), IKONOS (4–1 m), QuickBird (2.4–0.61 m) and WorldView-2 (2.4–0.46 m), freely available Landsat data of 30 m resolution play a crucial role in the classification of land use and land cover. This data is useful because Landsat sensors record blue, green and red light along with the near-infrared, mid-infrared and thermal-infrared light. Landsat data has been used to monitor water quality, glacier recession, sea ice movement, invasive species encroachment, coral reef health, land use change, deforestation rates and population growth. Landsat is also helpful in assessing the damage from natural disasters such as fires, floods and tsunamis, and subsequently help in planning disaster relief and flood control programs [35]. Many studies have investigated the spatial-temporal changes of the earth surface, which could be used in place of fieldwork data [36–39]. In 2D hydrological modelling, user has to assign several floodplain and river man-made structures. So these structures can be assigned from Landsat data with the help of Google Earth information because of the difficulty in identifying objects in 30 m resolution.

4. One-dimensional model

A flood occurs due to bursting of river's banks and the water spills onto the floodplain. The nature of the terrain around a river will tell how quickly rainwater reaches the channel. Upstream anthropogenic activities and topographic changes result in increased rates of sedimentation, which modifies the river geometries and results in downstream flooding. A river flood simulation helps us to understand the spatial-temporal changes in the nature of the river and its effects on the surrounding environment [28]. Hence, for river modelling, 1D modelling is essential to know the behaviour of river flooding. In 1D modelling, it is assumed that all water flows in the longitudinal direction. One-dimensional model represents the landscape as a sequence of cross sections and simulate flow to estimate the average velocity and water depth at each cross section [20].

4.1. Overview of HEC RAS

Hydrologic Engineering Centre's River Analysis System (HEC-RAS), well-known and widely used freely available software for 1D simulation with GIS compatibility, was developed by Ref. [40]. HEC-RAS can perform steady and unsteady flow hydraulics, sediment transport/mobile bed computations and water temperature modelling. The implementation of HEC-RAS requires huge amount of data. Several studies have been done using HEC-RAS, such as unsteady flow and sediment modelling [41], steady and unsteady flow simulations [42], discharge estimation [43], determination of freedom space for rivers [44], bedload transport computations [45], backwater height calculation [46], flood analysis [18, 44, 47], bedrock channel morphology variations [48], sediment transport simulation [49, 50], cross-section spacing testing [51], hydrologic simulation [52] and river water surface profile simulation [53].

4.2. Overview of MIKE 11

MIKE 11 is another widely used, but not free, 1D hydrological model. It can perform flood analysis, dam break analysis, water quality analysis, sediment transport analysis, optimization of reservoir and river structure operations, river salinity intrusion analysis, integrated flood and catchment modelling and wetland restoration studies [54]. Some of the studies found in the literature are river stage simulation [55], groundwater response investigation to overland flow and topography [56], lowland wet grassland modelling [57], water resource management [58], organic carbon loading simulation [59], dam impact on water and sediment [60] and runoff estimation [61].

4.3. Case studies of 1D model

Several case studies have been conducted using 1D models to show their capabilities in flood analysis. The estimation and selection of river cross section have been discussed in the above section. Apart from river cross-section selection, spacing between cross sections and in-channel vegetation effects on river geometry are also assessed by some researchers. Ali et al. [51] tested different cross section using LIDAR-based DEM in HEC-RAS without including any hydraulic structural across the river and found negligible difference between different cross-section spacing. Castellarin et al. [15] retrieved different number of cross section from high-resolution Digital Terrain Model (DTM) for their study. They found that once the satisfactory spacing is achieved depending on riverbed geometry, physical wave flood and tide shape, the inclusion of additional cross sections into the 1D hydraulic model does not necessarily improves the model accuracy. Ali et al. [51] studied the influence of downstream in-channel vegetation on cross-sectional geometry and found that with decreasing slope at the downstream, the velocity also decreases due to in channel vegetation and hence widening of river takes place. Mohammadi et al. [47] conducted a simulation of flood by suing HEC-RAS to estimate flood damages. Pietsch and Nanson [62] compared the performance of the artificial neural network (ANN) technique with MIKE 11 for hydrologic simulation and found better results by ANN in terms of goodness-of-fitness and Nash–Sutcliffe index while MIKE 11 showed good results in terms of RMSE. One-dimensional flow is the limitation of 1D model and hence it cannot give causes of flooding from floodplain.

5. Two-dimensional models

Two-dimensional hydraulic models are either based on finite element or finite volume to solve steady or unsteady flow equations in which water flows both longitudinally and laterally. The finite element method is a numerical procedure for solving differential equations in which continuous quantities are approximated by sets of variables at discrete locations forming a network [63]. Some of the widely used 2D models are HEC-RAS 2D, LISFLOOD-FP and FLO-2D.

5.1. Overview of HEC-RAS 2D

HEC-RAS 2D is a newly developed model and it has the ability to perform both in 1D and 2D hydrodynamic routing with unsteady flow separately as well as the combination of 1D and 2D unsteady flow by solving Saint-Venant or diffusion wave equation which allows user to work on larger river systems. For more details of this model, readers can pursue to model's reference manual [64].

5.2. Overview of LISFLOOD-FP

LISFLOOD-FP is a two-dimensional hydrodynamic model specifically designed to simulate floodplain inundation in a computationally efficient manner over complex topography. It is capable of simulating grids up to 10^6 cells for dynamic flood events and can take advantage of new sources of terrain information from remote sensing techniques such as airborne laser altimetry and satellite interferometric radar. The model predicts water depths in each grid cell at each time step, and hence can simulate the dynamic propagation of flood waves over fluvial, coastal and estuarine floodplains [65].

5.3. Overview of FLO-2D

FLO 2D is a volume conservation, flood routing and grid-based 2D model (economical as compared to MIKE 11) which uses a dynamic-wave momentum equation and a finite-difference routing scheme [66] and routes precipitation-runoff and flood hydrographs over unconfined surfaces and channels using either kinematic, diffusive or dynamic wave approximation to the momentum equation [67]. It can be used to delineate flood hazards and regulate floodplain zoning. While FLO 2D can simulate over-bank flows, it can be used to solve other flood-related problems, such as unconfined flows over complex plains and split channels, mud or debris flows and urban flooding [27].

5.4. Overview of MIKE 21

MIKE 21 is a 2D simple and faster Cartesian grid-based hydrological model for free surface flow, waves, sediment transport and environmental processes. The flood screening tool (FST) option introduces an additional numerical solver for it. A diffusive wave approach brings a simpler and thus faster numerical solution that enables even more rapid flood screening outputs [54].

5.5. Overview of TUFLOW

TUFLOW is also a grid-based 2D hydrodynamic model for free-surface flow. It has two products, viz., TUFLOW and TUFLOW FV in which TUFLOW FV has both 2D and three-dimensional (3D) flexible mesh solver. TUFLOW solves the full two-dimensional, depth averaged, momentum and continuity equations for free-surface flow using a second-order semi-implicit matrix solver. According to Ref. [68], the difference between TUFLOW and other 2D model is the inclusion of the viscosity or sub-grid-scale turbulence term that other mainstream software omits. A powerful feature of TUFLOW is its ability to dynamically link between their 1D and 2D networks.

5.6. Overview of XPSWMM

XPSWMM is a fully dynamic hydraulic and hydrologic modelling software that combines 1D calculations for upstream to downstream flow with 2D overland flow calculations which will help in understanding what truly happens to storm water system, foul water system or floodplain when waters flow, populations increase or catastrophic events hit. It allows integrated analysis of flow, pollutant transport and sustainable design measures in engineered and natural systems including ponds, rivers, lakes, overland floodplains and the interaction with groundwater [69].

5.7. Case studies based on 1D and 2D models

In 2D modelling, topographic data and its resolution are utilized in accurate modelling. However, the computational cost rises exponentially as the resolution goes finer [11]. Horritt [70] conducted 2D finite volume model with mesh resolution ranges from 2.5 to 50 m and found better results in high-resolution mesh. Chen et al. [11] proposed an approach by using multiple layers on coarse grid cell and found more accuracy with fine grid cell in same processing time which will reduce the cost of modelling. Chen et al. [71] built features in coarse grids by using the building coverage ratio (BCR) and the conveyance reduction factor (CRF) parameters in a 2D model to simulate flooding in urban areas. They found that the proposed model can minimise the errors due to terrain averaging and provide a much better accuracy of modelling results at a marginally increased computing cost. Liu et al. [56] analysed the influence of groundwater and topography on the response characteristics of overland flow by using combined 1D and 2D model in arid region. They successfully used fractal-wavelet approach to analyse the temporal characteristics of groundwater. Neal et al. [21] used three 2D explicit hydraulic models (defined as simulating diffusive, inertial or shallow water waves) to know the physical complexity needed in flood inundation simulation. They found that the diffusive-type model required much longer simulation times while inertia model was the quickest. Differences in simulated velocities and depths due to physical complexity were within 10% and simpler models were unable to simulate supercritical flows accurately. Quiroga et al. [72] used the application of 2D model in flood analysis and found good performance when compared with satellite image of the flood event. They found that the simulation provide information such as water depth, flow velocity, temporal variation of the flood and specific locations where water begins to overflow. Vozinaki et al. [73] compared the combined

1D and 2D models by using high-resolution DEM to check the results accuracy and found success in estimation of accurate flood hazard area. Some other recent studies of 1D modelling are debris flow simulation [74–76], dam break simulation [77], hydrodynamic modelling [78] and mudflow simulation [79].

6. Three-dimensional model

One- and two-dimensional hydrological models have some limitations such as the assumption of hydrostatic pressure, more horizontal length than vertical length, viscous shear stresses and bed friction on fluid components, roughness implementation on grid plane and macro-effects of changes of channel shape and direction but these limitations can be improved by 3D models [80]. Some of 3D hydrological models are as follows.

6.1. Overview of FLOW 3D

FLOW-3D is a powerful and highly accurate computational fluid dynamics (CFD) software that gives engineers valuable insight into many physical flow processes. It allows flexible gridding system, which is referred to as free-gridding because grids or geometry can be freely changed each independent of the other. FLOW-3D accurately predicts the detail of severe storm and tsunami wave run-up on coastal structures and is used for flash flood and critical structures flood and damage analysis. It is also used in large hydroelectric power projects and small municipal wastewater treatment systems, which is helpful in finding accurate results for testing design options, reduction in complexity and focussing efforts on optimized solutions [81].

6.2. Overview of MIKE 3

MIKE 3 is developed on the same module of MIKE 21, which provides the simulation tools to model 3D free surface flows and associated sediment or water quality processes. It also has a flexible gridding system. The ideal applications of MIKE 3 are mostly associated with coastal and marine hydrological modelling, lake hydrodynamic, ecology and environmental impact assessment of marine infrastructures.

Some studies used 3D models in the modelling of river width vegetated floodplain [82], simulation of curved open channel flows [83] and modelling for small debris flows [84]. Various 1D, 2D and 3D models are listed in **Table 4** with their case studies references.

S. No.	Model	References of related studies
1	HEC RAS	[18, 41–53]
2.	MIKE 11	[55–61]
3.	HEC RAS 2D	[72, 73, 85]
4.	LISFLOOD-FP	[17, 86–89]
5.	FLO 2D	[66, 67, 90, 91]

S. No.	Model	References of related studies
6.	TUFLOW	[92–95]
7.	MIKE 21	[96, 97]
8.	XPSWMM	[98–102]
9.	FLOW 3D	[103, 104]
10.	MIKE 3	[105–107]

Table 4. Hydrological models with their related study references.

7. Uncertainty in hydrological modelling

Earth processes in which changes occur in land, air and ocean in different environment and at different scales are very complex. River and floodplain processes have been studied through hydrological modelling which simplify the complex reality of Earth surface. However, hydrological model have some uncertainties, which should be included to understand the accurate causes and effects of flooding in both river and floodplain. River and floodplain modelling are characterized by uncertainties in input and model parameters, model structures and model calibration. Precipitation, one of the most basic input parameters in rain-fall-runoff modelling, is taken as a parameter with uncertainty by some recent studies. The discontinuity in precipitation has already been discussed in the previous sections. McMillan et al. [108] highlights the dependency of rainfall error on the data time step in hydrological modelling. Benke et al. [109] analysed the impact of parameter uncertainty on predictions of streamflow for a water-balance hydrological model and found that the shape (skewness) of the distributed parameter’s uncertainty had a significant effect on model output uncertainty. Poulin et al. [110] investigated the effects of model structure and parameter results from different events on the uncertainty related to hydrological modelling in climate change impact studies and concluded that the impact of hydrological model structure uncertainty is more significant than the effect of parameter uncertainty. Dobler et al. [111] studied the uncertainty of model parameter and hydrological projection in different models and found that the hydrological projection uncertainty varied with the choice of models affected by choice of model parameters. Engeland et al. [12] explore the effect of input uncertainty and poor observation quality on hydrological model calibration and predictions. They found that insufficient information of input parameters affects model parameters and hence results in poorer calibration and prediction. Therefore, from the above discussion it can be concluded that model uncertainty should be given utmost importance for prediction of accurate results.

8. Conclusions

Flood is the most devastating natural hazard in the world. It could be a cause of complex topographic and climatic changes on the Earth. Hydrological modelling is a useful tool to

determine dynamic behaviour of flooding, its causes and effects. Based on the above discussion, this chapter concludes with the following key points:

- Precipitation is most important factor in flash flood modelling which should be used without any discontinuity. Basin shape, size, slope and stream density, spatio-temporal land use and land cover changes are important factor in controlling runoff frequency.
- Soil characteristics and the presence of decomposing plant material on the surface affect infiltration rate, which should be considered in hydrological modelling for accurate results.
- In-channel vegetation should also be considered in hydrological modelling which effects in changing downstream channel geometry.
- Basins of any study area should be prioritized on the basis of flood risk prior to hydrological modelling and then it has to be carried out in prioritized basins, which will save simulation time and will give better results.
- In spite of the use of high-resolution topographic data, which increases processing time and computational cost, freely available ASTER GDEM can be used by including multiple layers of parameters, which will give accurate results, less processing time and low computational cost.
- In data sparse environment, cross section can be selected as per the above-mentioned methods, and land use and land cover classification can be carried out from freely available Landsat data with the help of Google Earth information.
- Overview of widely used 1D, 2D and 3D hydrological models with their case studies are also helpful in knowing the usage of these models for different flood-related studies.
- At last, uncertainties of hydrological modelling were should be taken into account while modelling to enhance the results.

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