Chapter 2
Flood Inundation Modelling in Data-Sparse Flatlands: Challenges and Prospects

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Abstract In the last three decades, many sophisticated tools have been developed that can accurately predict the dynamics of flooding. However, due to the paucity of adequate and immediate infrastructure, this technological advancement did not benefit the vast ungauged flood-prone regions in the developing countries in a major way. This chapter explores the improvement in methodology that is essential for utilising recently developed flood prediction and management tools, particularly in the flat deltaic landscapes in the developing world, where ideal model inputs and validation datasets do not exist. The issue of appropriate model selection assumes greater significance when modelling is carried out without the availability of ideal inputs and validation datasets in the largely ungauged river basins. This discussion include key considerations for undertaking flood inundation modelling in data-sparse environments and can be valuable for flood managers and hydrologists engaged in tackling this problem with limited resources.

Keywords Hydrodynamic modelling · Coarse model inputs · DEM selection · The Ganga delta

1 Flood as a Global Natural Hazard

Floods account for approximately one-third of global natural hazards, and more people are adversely affected by flooding than any other geophysical phenomenon (Smith & Ward, 1998). On average, 20,000 people lose their lives due to flooding each year, and it affects 75 million people globally, most of whom become homeless (Smith, 2001). These global figures mask much regional variation in the occurrence of floods, the causes and the consequences on the populations. Adhikari et al. (2010) compiled a digitised global flood inventory for the period of 1998–2008 that reveals some important facts about different causes of flooding, the spatial variation and

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frequency of occurrences. According to this database, heavy rain, monsoon rain and tropical cyclones were reported as the causative factors for 64%, 11% and 6% floods, respectively. These types of meteorological phenomena occur only in the tropical and subtropical regions where most of the developing countries are located. This database further reported that seven of the top ten countries with most flooding events reported between 1998 and 2008 were outside the industrialised world and that Asia and Africa have the highest percentage of reported flood events each year. Jonkman (2005) pointed out that the floods caused by Asian rivers claim the most lives and affect more people than any other region in the world. Flood-affected population in the developed world have the means to combat the extreme natural events through better infrastructure, health care, and functional flood warning systems (Allenby & Fink, 2005) while in the developing countries vulnerable populations lack the capital resource to develop sustainable protection mechanisms or rebuilt their damaged infrastructure after a major flood event.

The deltas of large rivers in the tropical regions are particularly flood prone. Such landscape is characterised by very low gradient of land, numerous branches and sub-branches of the main channel and a near absence of local-level hydrological and terrain-related information that are crucial for predicting the extent and depth of fluvial inundation. The Ganga delta, spreading across the Indian state of West Bengal and the southern part of Bangladesh, offers a typical example of such terrain. This region urgently need to develop a flood-prediction capability at an affordable cost for creating an early warning system and adopting structural (such as building embankments) and nonstructural (such as floodplain zoning) measures for flood management.

2 The Issue of Limited Data in Flood-Prone Regions

2.1 Prevailing Mismatch in Scientific Advancement and Global Availability of Suitable Datasets

Hydrodynamic models are the standard tools for predicting fluvial inundation. Streamflow data and topography of channels and floodplains are the two most significant model inputs that influence the flow hydraulics and modelled flood extents. The science of inundation modelling has transformed rapidly in recent years from a 'data-poor' to a 'data-rich' discipline with a gradual shift from developing more physically based models to simple ones that can effectively harness the increasing availability of high-resolution earth observation data to improve on their predictions (Bates, 2012). Constant improvement of very high-resolution terrain data form of LiDAR survey and all-weather capable synthetic-aperture radar (SAR) images for calibrating and validating distributed performances of flood-inundation models has advanced the flood prediction capability in the developed world significantly.

The study by Bates et al. (2006) in a 16 km reach of the River Severn in the United Kingdom is a typical example of the data-intensive inundation modelling approach. This study used LiDAR-generated DEMs in combination with a series of airborne synthetic-aperture radar (ASAR) images captured opportunistically during the peak and recession limb of the flood hydrograph in order to calibrate and validate flood models. The LiDAR DEM used was of <1 m horizontal resolution with a vertical root mean square error (RMSE) of 0.079 m. Elevation is measured by differential GPS points of approximately 0.01 m vertical accuracy that was used as reference spot heights for obtaining the RMSE value of the DEM while the ASAR images were of 1.2 m resolution. This dataset was further supplemented with space-borne RADARSAT images, upstream and downstream gauging records at 15 min intervals and extensive field data collected during the actual flood event.

The quality of LiDAR data has improved further in recent years. Inundation modelling has been performed successfully at 10 cm grid size for a small piece of urban land by using very high-resolution LiDAR data captured with vehicle-mounted terrestrial laser scanner (Sampson et al., 2012). High-resolution SAR data are typically available at ~25 m ground resolution, but Mason et al. (2009) utilised TerraSAR-X images with 3 m resolution for detecting flood water in the urban environment. The availability of fine resolution inputs, particularly the fine-resolution validation data from SAR imageries help reduce the equifinality arising from the difficulty in differentiating between different model physics and parameters and provided a more controlled environment for comparing the effect of including individual hydraulic process in the code (Bates, 2012). Thus, it is clear that a steady trend of advancement in the quality and coverage of the required data has led to marked improvement in the science of inundation modelling. Nevertheless, the major flood-prone areas in the world are not able to benefit much from this development of state-of-the-art inundation models given that LiDAR-derived terrain data are almost always unavailable in the developing countries due to the prohibitive cost of acquiring them (Sanyal & Lu, 2004). This scenario leaves us with the option of using freely available DEMs such as the Shuttle Radar Topography Mission (SRTM) DEM or the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) for defining the model geometry.

2.2 *Applicability of SRTM DEMs for Flood Inundation Modelling*

Although Sanders (2007) demonstrated the potential of employing the SRTM DEM in inundation modelling and Manfreda et al. (2011) highlighted the reliability of this data to identify flood-prone regions with a modified topographic index, it is well known that these terrain data contains considerable noise (Bhang et al., 2006). Such noise nullifies the hydrodynamic exchange during the coupling of 1-D and 2-D flow in the recent improved models (Mohanty et al., 2020). A global performance assessment study of the SRTM data by Rodriguez et al. (2006) revealed an absolute height error of 6.2 m, 5.6 m and 6.2 m for Eurasia, Africa and South America, respectively. The SRTM DEM is also dated (acquired in the year 2000) and creates problem in areas where previous events have known to have modified the floodplain considerably (Schumann & Bates, 2018).

The ASTER GDEM is reported to have significant anomalies and much higher RMSE than the SRTM DEM when compared with LiDAR-derived elevation data derived from ICESat (Reuter et al., 2009) and is not suitable for inundation modelling in any manner. Due to their overall vertical inaccuracies, global DEMs are not deemed suitable for detailed flood inundation modelling in local and regional scale (Yan et al., 2015). Having said that, it is worth noting that in the flat floodplain areas, SRTM DEM was reported to have a vertical accuracy of better than 2 m (Schumann et al., 2013). However, modelling flood inundation in large rivers flowing over extremely gentle gradient with commonly anabranching channel patterns and slow-moving flood waves are particularly sensitive to the vertical accuracy of the terrain data (Jarihani et al., 2015).

In spite of all the constraints mentioned above, there is an increasing trend of utilising freely available terrain data for hydraulic modelling of streamflow. Due to the coarse nature of the available terrain data (e.g., SRTM DEM), the majority of these studies has been undertaken at continental scale. For example, Yamazaki et al. (2012a) applied a global river model, CaMa-Flood (Yamazaki et al., 2011), to model the seasonal cycles of water level elevations in the Amazon River using the SRTM DEM as the terrain input and the simulated water surface elevations were compared with Envisat altimetry. Development and application of flow routing and inundation models in the data-sparse regions of the world is mostly confined to the very large continental river basins such as the Amazon (da Paz et al., 2011), Congo (Jung et al., 2010), Niger (Neal et al., 2012a) and Ob (Biancamaria et al., 2009). The abovementioned studies are primarily engaged in simulating seasonal or annual cycle of river discharge and water level or even water budget and flooding pattern of large wetlands of the Niger River (Zahera et al., 2011) and the Nile Basin (Petersen & Fohrer, 2010).

A number of novel attempts have been reported to deal with the low resolution of the freely available DEMs that were used in these investigations. Paiva et al. (2011) developed a GIS-based algorithm that includes extraction of river cross-sections, delineation of river networks and catchments from the SRTM DEM and used geomorphic principles to estimate the river width and depth. Yamazaki et al. (2012b) proposed a pit removal strategy to reduce the anomalies in the SRTM data arising from vegetation canopy and sub-pixel structure and reported an improvement in the simulated water surface elevation with the adjusted DEM in terms of agreement with the observed records. Neal et al. (2012a) demonstrated how a sub-grid scale representation of a channelised portion of the flow can help to simulate streamflow in narrow channels that cannot be captured in the low-resolution global DEMs. However, this model still needs measurements about channel depth and width to derive the empirical relationship for estimating channel-bed elevation from bank elevation and channel width. The slope break approach was employed in estimating channel bathymetry in a stretch of the Po River in Italy, which led to tangible improvement in the performance of a hydrodynamic model (Domeneghetti, 2016).

Since the X and C band radars used in the SRTM instrument do not penetrate the canopy, the SRTM DEM captured the tree top elevation rather than the surface at any place with dense foliage. Recently, global percentage vegetation map is derived from MODIS satellite images, global vegetation height map and sparse, but very accurate elevation points obtained from IceSat laser altimeter have been used to remove the vegetation artefacts from the 90 m version of SRTM DEM for producing a 'bare-earth' variant of the dataset (O'Loughlin et al., 2016). The global vertical RMSE of this product was reported to have gone down from 14 m to 6 m. Yamazaki et al. (2017) created Multi-Error-Removed Improved Terrain DEM (MERIT DEM) from the SRTM dataset by removing absolute bias, stripe noise, speckle noise and tree height bias. Such improved DEM was used to create a global river topography database, known as the MERIT Hydro (Yamazaki et al., 2019).

2.3 *Applicability of Other Low-Cost Sources of DEMs in Inundation Modelling*

Few attempts were made to generate terrain data from relatively affordable stereo satellite imagery sources for reach scale inundation modelling in the developing world where generally the SRTM DEM is the best available option. For example, Tarekegn et al. (2010) generated a DEM of 15 m resolution from ASTER imagery using ERDAS LPS digital photogrammetry software for 2-D hydrodynamic simulation of flooding in the Ribb River in Ethiopia but reported only 30.5% match between the simulated flooded extent and observed flood extent derived from a MODIS image. Considering the previous studies regarding the accuracy of the ASTER DEM data, this result is not surprising.

Low-cost Cartosat-1 stereo satellite imageries (2.5 m spatial resolution) from Indian Remote Sensing Satellites (IRS) were found to produce more accurate DEMs than the SRTM or ASTER data when compared with surveyed ground control points (Rawat et al., 2013). Sarhadi et al. (2012) used Cartosat-1 images to create high-resolution DEM of 2.5 m grid spacing in order to perform inundation modelling in the mountainous region of Iran and reported a high accuracy in the modelled flood extent. Cartosat-1 imageries were used in conjunction with 42 differential GPS (DGPS) ground control points (GCPs) to create a DEM of 30 m resolution for modelling floods in wide valleys (width $>$ 500 m) of the Mahanadi River, India, and the model performed reasonably well when compared with the results derived from surveyed cross-sections (Jena et al., 2016). In a similar set-up in the Damodar River, India Sanyal et al. (2013) reported that only seven surveyed cross-sections for a 100 km reach were sufficient to supplement SRTM DEM for accurately predict downstream water stages during high magnitude flow events provided the water remain confined within the banks/embankments. However, for slightly narrower channels (width ~ 300 m), the DEM created from IRS Cartosat-1 stereo images with 10 GCPs were not found to be accurate enough for simulating widespread floodplain flow and had to be supplemented with a series of surveyed cross-sections for the detailed representation of the channel (Sanyal et al., 2014a).

It is worth noting that a mass-produced DEM derived from Cartosat-1 imageries has been generated by National Remote Sensing Centre (NRSC), India, covering the entire India, which are available for download free of cost. The vertical accuracy of CartoDEM was reported to be 5.2 m and 7.9 m for plain and hilly terrain, respectively, when compared with ICESat Glass data (Muralikrishnan et al., 2013). The bias in the SRTM DEM was found to be more systematic than CartoDEM. Kumar et al. (2019) noted that a corrected version of the SRTM data improved the accuracy of a 1-D hydrodynamic model while similar effort to modify the CartoDEM resulted in degraded prediction. In spite of these limitations, it is encouraging to note that Mohanty et al. (2020) found the performance of CartoDEM in hydrodynamic modelling almost at par with LiDAR DEMs and highly recommended its use for India.

2.4 Creating Accurate River Terrain Model from Sparse Data

The most significant determinant of the performance of a hydraulic model is the accuracy in the representation of the channel geometry (French & Clifford, 2000; Pappenberger et al., 2005). Creating a continuous and detailed terrain data for the channel is a requirement for 2-D hydrodynamic models. Even for the 1-D models, a continuous DEM including the channel is often required to derive the extent of inundation where the terrain height is subtracted from the simulated water level at each cross-section to identify the wet cells. Creating a reasonably accurate river terrain model in data-sparse regions can be quite challenging because of the narrow width of the channel in comparison to the coarse resolution of the freely available DEMs. Particularly, for the SRTM DEM, the problem is aggravated by voids in the wet part of the channel arising from specular reflection of radar backscatter from calm water. In the 'finished' versions of the SRTM DEM, which have less void and noise, any river with more than 183 m of width was monotonically stepped down at the direction of flow (Slater et al., 2006). This processing led to step-like appearance in channels along their longitudinal profiles and made them difficult to use, at least in the reach scale.

Merwade et al. (2008a) pointed out that linear interpolation of the available surveyed cross-sections for creating a continuous river terrain model is not straightforward due to various facts including bends in the river and imperfect location of the cross-sections. In addition, the existence of channel islands not captured by enough number of cross-sections and inadequate representation of channel thalwegs by the bathymetric surveys also make the interpolation a challenging task. Merwade et al. (2006) reported that in a flow-oriented coordinate system, the performance of anisotropic spatial interpolation techniques resulted in significant reduction in RMSE as compared with the conventional interpolation techniques such as nearest neighbour or kriging. This study proposed elliptical inverse distance weighting, a modified version of conventional inverse distance weighting (IDW), to take advantage of the flow oriented coordinate system as the channel bed morphology is essentially anisotropic due to greater variability of bed elevation perpendicular to the flow direction than along it. However, the investigation used spatially irregular bathymetry data collected by boat-mounted acoustic depth sounders rather than linear channel cross-sections. Even the isotropic techniques of interpolation were reported to perform well if the surveyed bathymetry data are de-trended and transformed into a flow-oriented coordinate system (Merwade, 2009). However, after experimenting with various interpolation techniques in a flow-oriented coordinate system, Legleiter and Kyriakidis (2008) commented that the density of surveyed points exerts primary control over the accuracy of interpolated surface and the RMSE of the interpolated surface has a strong relation with the spacing of the cross-sections.

All the interpolation techniques mentioned above are likely to create accurate interpolated surfaces of the channel if there is adequate data in the form of irregular elevation points or linear surveyed cross-sections. In the case of anabranching and anastomosing rivers with a number of flow bifurcations and large river islands, the abovementioned methods may not perform well (Merwade et al., 2008a). For a successful implementation of the aforesaid interpolation techniques to capture the flow diversion near the river bifurcations, very high density of surveyed points will be required, and therefore these methods may not be suitable for use in a complex fluvial system, especially in the flat deltaic environments of the developing countries.

3 Inundation Modelling at Regional and Reach Scales with Limited Data

In general, there is a lack of focus on flooding as a natural hazard when it comes to hydraulic modelling in data-sparse regions. When we develop a tool for a flood prediction and warning system, it is conventionally focussed on modelling extreme flow events with an accuracy that is acceptable in flood management and planning practices. There are very few case studies at regional scales outside the industrialised countries for river basins that are fairly large (length $>$ 500 km) but not of continental scale such as the Amazon and of cases that regularly inundate densely populated floodplains. Use of the global DEMs for routing high-magnitude floods at a regional scale is likely to require some additional reference data in order to correct the systematic bias and noise present in them and increase the details of topographic representations where it is absolutely necessary. Due to this reason, there is almost no scientific literature on hydrodynamic predictions of inundation that are of fluvial origin in the Ganga Delta. Storm surge modelling in the Bay of Bengal Coast of Bangladesh was carried out (Deb & Ferreira, 2018; Islam et al., 2019) including prediction of the probable impacts of climate change (Rahman et al., 2019). However, lack of accurate terrain data and information on the tidal influence led to a challenging environment to develop a functional hydrodynamic model for the Ganga Delta.

Few attempts were made to simulate river flows in regional scales by correcting the vertical errors in SRTM DEM using spot heights from topographic maps of 1: 50,000 scale in sparsely gauged parts of the Mahanadi (Patro et al., 2009) and the Brahmani Rivers (Pramanik et al., 2010) in India. Casas et al. (2006) evaluated the effect of quality of input terrain data on the accuracy of predicted water surfaces using HEC-RAS model. Although this study reported poor performance of contour maps with 5 m intervals in comparison with high-resolution LiDAR DEMs, it is interesting that the observed error in predicted water surface reduced quite dramatically as the flow crosses the bank limit and lack of river channel bathymetry becomes less significant. Adding GPS control points to the less accurate contour-derived TIN model improved the predicted water-surface elevation by 4.5 m. This finding is particularly encouraging with a view to employing relatively low-resolution DEMs for large flood prediction, which can be supplemented with GPS surveyed control data to improve accuracy.

The majority of the inundation modelling that is focussed on analysing flood risk is conducted at the reach scale (<20 km). Generally, a major flood is considered for which detailed topographic data for the flood-prone reach is available. There is an acute lack of literature that deals with this kind of study outside the industrialised countries because the globally available DEMs are normally too noisy to accurately simulate floodplain flow at this scale. One such attempt has been made by Masood and Takeuchi (2012) for creating a flood risk map for part of Dhaka City in Bangladesh where the SRTM data was resampled into 30 m resolution. The areas which experienced significant landfilling since the time of the SRTM mission were identified, and the corresponding grid cells were raised to match the current topography. The nature of the reach scale studies performed with no access to LiDAR DEMs or other comparable sources in developing countries such as Bangladesh (Masood & Takeuchi, 2012), Iran (Sarhadi et al., 2012) or Thailand (Keokhumcheng et al., 2012) was probabilistic. The flood events considered were only designed events with a high return period, not the actual ones, and the modelled flood extents were compared with the observed flood extent of a typically large event rather than the actual satellite overpass.

A more rigorous validation of the results in the reach scale derived from freely available DEMs is necessary. It is evident that the SRTM or ASTER DEMs in their available form are not suitable for modelling widespread floodplain flow at reach scale. Even for applications in regional scale such as Patro et al. (2009) or Pramanik et al. (2010), the SRTM DEM was modified with reference ground control points before employing in 1-D hydraulic models. For undertaking hydraulic modelling at the reach scale without access to very high-resolution terrain data, some researchers have tried to combine elevation information from a variety of sources to increase the detail of channel and floodplain representation. For example, Tate et al. (2002) exported the ground surveyed XYZ data from HEC-RAS model into real-world coordinates and merged them with a relatively low-resolution DEM to get more detailed representation of the channel and embankments. The assumption of straight-line cross-sections is one of the limitations of this approach as the cross-sections are generally doglegged in shape. Shapiro and Nelson (2004) edited and merged terrain data from various sources and created a TIN with higher density of elevation points at or near the channel and less resolution further away. Sanyal et al. (2014a) created a suitable DEM by combining accurate elevation information from SRTM DEM, Cartosat-1 stereo imageries and DGPS-aided surveys of channel cross-sections for flood inundation modelling at reach scale.

4 Choice of the Model and the Required Level of Complexity

A number of benchmarking studies depending on the 1-D versus 2-D code (Horritt & Bates, 2001), scale of the model domain (Fewtrell et al., 2008), the nature of the numerical solution of 2-D hydrodynamic models (Horritt et al., 2007) and ways of setting up the parallel computing environment (Neal et al., 2010) were carried out in the past. One-dimensional hydrodynamic models are computationally efficient and can produce accurate water surface elevations without very high-resolution terrain data. However, high-resolution terrain data are required for modelling extensive floodplain inundation. Although 1-D models were found to perform equally well as the 2-D models in certain cases (Horritt & Bates, 2002; Alho & Aaltonen, 2008), generally 1-D models are less efficient in simulating the lateral diffusion of flood waves in the floodplain because of the discrete representation of the topography in the form of cross-sections (Hunter et al., 2008). It is also not technically sound for modelling backflow in floodplains (Merwade et al., 2008b). In addition, the roughness coefficients, which are required to account for the energy loss from a variety of sources, depend on the dimensionality of coding and level of process representation (Lane & Hardy, 2002). The roughness parameters estimated from field data are more likely to work well in physically consistent 2-D models than simpler models (Hunter et al., 2007).

Physically-based more complex finite element codes were also found to be less sensitive to the resolution of the terrain model and therefore are effective in containing the uncertainty in the model outcomes (Cook & Merwade, 2009). There is an element of non-stationarity of the friction parameter arising from the variation in the magnitude of the flood under consideration and physically-based fully 2-D models can keep the effect of this factor low (Horritt et al., 2007). Hunter et al. (2008) compared the performance of a number of diffusive and shallow water codes in an urban setting in Glasgow and noticed variations in the modelled depth and flooded extent depending on the hydraulic process representations and types of numeric solvers in use. Process representation was not always found to influence the model outcome decisively. Sanyal et al. (2014a) compared the performance of a reduced complexity approach-based 1-D and 2-D-coupled LISFLOOD-FP model with a fully 2-D finite element TELEMAC2D in an anabranching river system. Results show that the latter was less sensitive to the limited accuracies of the terrain data and fared better than the former in handling the flow-splits in the channels.

Often the subtle modelling decision such as methods of downgrading the resolution of a DEM from 10 to 50 m can have more effect on model outputs than selecting models with different degree of complexity (Neal et al., 2012b). However, while working with low-gradient river systems using global DEMs, Jarihani et al. (2015) reported that the performance enhancement with finer DEM grid size was nonlinear and <120 m grid size did not provide additional benefit when the associated increase in the computational cost was taken into account.

The most important parameter after topography in influencing the flow in natural channels and overland inundation is the roughness of the terrain (Straatsma, 2009). Manning's roughness coefficient (n) is the most common form of roughness parameter used in modelling hydrological studies. Although n is primarily used to account for the energy loss due to friction at the boundary of the flowing water and terrain surfaces, it is often used for compensating for the physical processes that are not considered by the governing equations of a hydrological/hydraulic model (Morvan et al., 2008). Various studies have used measured flow velocity, depth and cross-sectional area to determine bottom friction with numerical modelling (Stephen & Gutknecht, 2002; Mailapalli et al., 2008; Aricò et al., 2009). In most of these studies, terrain was used as inputs, measured flow data as boundary conditions, and the value of n was calibrated to achieve a best-fit to measure water surface data.

The extent to which a hydrodynamic model is sensitive to roughness and geometry uncertainty partially depends on the dimensionality of the model structure as this factor represents the geometry in different manners (Lane et al., 1999). However, Lane (2005) argued that roughness is strictly a component of topography, and better parameterisation of topography would ultimately reduce the sensitivity of hydrodynamic models to n values. This view has been further put forward by Medeiros et al. (2012) who concluded that parameterising floodplain roughness on the basis of the detailed terrain configurations and the presence of obstruction would be more effective than relying on remotely sensed LULC information for inundation modelling. We often change the description of roughness with changes in scales to compensate the effect of topography on processes influencing interaction between the surface and the terrain, hence implicitly recognising that roughness is scale dependant (Lane, 2005). The published sources for recommended values of n were commonly derived from plot scale experimental set-ups or small controlled experimental catchments, which makes it unreliable to use in numerical modelling involving large rivers.

5 Treatment of Uncertainties

A systematic estimation of the predictive uncertainty in a hydrodynamic modelling experiment is an essential component of any flood prediction mechanism. Uncertainty analysis in inundation modelling and flood risk analysis is important because it improves the evaluation of risk by identifying the sources of variation in model predictions, and even can influence decision-making on flood mitigation (Merz et al., 2008). It can also result in serious error in hazard assessment (Di Baldassarre et al., 2010). Merz et al. (2008) further pointed out that if the uncertainty component of a particular prediction is found to be too large for a reasonable decision-making process, it may highlight the necessity of further research to understand the physical process of inundation in that study area. Uncertainty assessment is more essential in the context of data-sparse situations in order to know the level of confidence we can attach to a particular prediction that was derived from model inputs of coarse quality and approximate measurements. The proportion of area in a model domain affected by the uncertain flood prediction increases with increasing uncertainties in the model inputs and choice of techniques and vice versa (Merwade et al., 2008b). Particular forms of channel configuration in a flood-prone reach, such as an anabranching pattern, sometimes require special attention for uncertainty assessment (Sanyal et al., 2014b). An uncertainty assessment is important in order to know the extent to which the modelled flood extents are affected by (1) each of the uncertain inputs and modelling considerations, (2) the spatial dimension of the effect of changes in each of the uncertain variables and (3) the nature of propagation of each uncertain variable in the inundation process and its effect over the combined state of uncertainty of a prediction (Jung & Merwade, 2012).

The generalised uncertainty likelihood estimation (GLUE) (Beven & Binley, 1992) methodology has been widely used in inundation modelling by using time series of river stages from gauging sites (Hunter et al., 2005) as well as distributed observed inundation patterns derived from satellite images (Horritt & Bates, 2001) and aerial photographs (Romanowicz & Beven, 2003). Uncertainty in the topographic data, especially a continuous surface interpolated from spot heights and contours, can have significant impact over hydraulic variables such as velocity and depth of inundation in small scale (Wilson & Atkinson, 2005a, b). The inundation boundaries depicted in flood hazard maps have inherent uncertainties related to the grid size of DEMs and the steepness of the gradient of the land perpendicular to the streamflow direction (Brandt, 2016). Channel cross-sections are sometimes difficult to measure in some locations (Sefe, 1996); sometimes they are not stationary (Callede et al., 2000) and particularly prone to modification after major floods.

Uncertainty in the measurements of observed data such as time series of stage/discharge records or flood-extent maps derived from airborne or spaceborne platforms may affect the computation of predictive uncertainty. Such error may also add a significant amount of uncertainty in estimating design flood events (Di Baldassarre et al., 2012). As the reference vertical datum for the river gauges are often based on local datum and not related to a global geoid model, it is difficult to make a direct comparison between simulated river stages and an observed one (Hall et al., 2011, 2012). For data-sparse regions, we commonly use freely available global DEMs such SRTM or ASTER GDEM that are generated from global geoid models such as EGM96. Survey authorities in developing countries featuring large flood-prone deltaic tracts generally do not follow a geoid model for preparing large-scale topographic maps and geodetic control networks. For example, in India, no geoid model is used for determining the vertical datum, and there is no straightforward way of converting the local mean sea-level information into an established geoid (Agrawal, 2005). This factor introduces uncertainty in the observed river-stage information when global DEMs and surveyed data collected through differential GPS is used in models to predict water-surface elevations.

6 Conclusion

The overall message from this discussion is that when the general goal is to predict the dynamics of riverine floods in the deltaic flatlands with limited data, particular attention should be paid to the choice of the model in relation to the available data and hydraulic characteristics of the event. Adaptations are necessary to create inputs for the models that have been primarily designed for areas with better availability of data. Freely available geospatial information of moderate resolution can often meet the minimum data requirements of hydrological and hydrodynamic models if they are supplemented carefully with limited surveyed/measured information. The amount of uncertainty in these types of prediction setups for extreme streamflow events was not found so great that it would discourage scientific community from using them under severe data constraint. The need of the hour is to develop highly skilled human resource for tackling this challenge. It is also crucial for the governments of respective countries to take an initiative towards establishing a hydrologic monitoring infrastructure and a framework of surveying channel bathymetry of the major flood-prone rivers.

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