Reverse engineered flood hazard mapping in Afghanistan: A parsimonious flood map model for developing countries

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ABSTRACT

Most flood models are based on advanced algorithmic and multiple data requirements that are sometimes difficult to apply in developing countries. These feed-forward models cannot be applied to large areas and can lead to extreme over/under estimations in some developing countries due to extrapolation from inadequate datasets where each additional parameter adds further uncertainty. This study proposes to employ a parsimonious model that only relies on adequate available data reducing forward-uncertainty-propagation. A “reverse engineering” approach that relies on past inundation depths does provide a solution for flood hazard mapping where extracting the flood extent of extreme floods is the primary goal and where only inadequate hydrological input data are available. The feedback method was successfully deployed to create the nationwide Afghanistan Flood Hazard Map (AFG-FHM) at a scale of 1:100,000 using a high-resolution digital elevation model, sample measurements and Dartmouth Flood Observatory past flood data. This paper describes the parsimonious flood map model and general methodology employed to create the AFG-FHM, as it is a robust method to generate extreme inundation outlines, which can be utilised in other developing nations as well.

1. Introduction

Most river flood inundation models are based on advanced algorithmic and multiple data requirements that are generally created in the developed world. These models can be difficult to apply in developing countries. Not only do these models require vast amounts of high-quality input data; they are also commonly based on the premise of available and documented historical flood maps that primarily need further refinement. For this reason most hydraulic flood models are intended for small-area flood mapping and for usage on short river stretches with few tributaries.

In least developed countries (LDCs) and some developing countries, input data for advanced flood modelling are not available or data lack temporal and positional accuracy (UNFCCC, 2007). Particular weather events are commonly not attributed to creating floods, and moreover accurate maps of past flood events that can indicate which areas are in need of flood hazard mapping are not available. Even particular rivers are not attributed to being flood prone, but floods are rather ascribed to a district or province level (Hagen and Teufert, 2009). In some countries such as Afghanistan, even basic information is missing that describes the type of floods, the flood causes, or the temporal window when floods can generally be expected. The scarcity of records of the stream-flow characteristics in the Afghan Helmand Basin (Williams-Sether, 2008) is a good example of this.

Developing countries are, however, in need of rudimentary flood hazard maps (Rabindra et al., 2008). These can help aid agencies, both governmental and non-governmental, to coordinate their efforts in response to flooding events (Hagen and Teufert, 2009). Construction of buildings and infrastructure in flood-prone areas can be avoided, and rudimentary flood hazard maps can assist insurance companies with risk assessment. A nation- or region-wide map can indicate which areas need further investigation and where mitigation studies might be useful. Medium-scale flood maps can be further refined by in-situ data collections such as river flow data or river cross-sections with more advanced inundation models such as HEC-RAS or Lisflood FP.

1.1. Problem statement

At present, no reliable method exits to generate nationwide flood maps (areas >50,000 km²) for developing countries that
have sufficient accuracy to be further utilised in follow-up studies. Thus current studies commonly focus on one particular area and try to generate from an inadequate base data set all data that advanced flood models require. A data set that not only has limited spatial accuracy but also temporal deficiencies and commonly cannot be linked to past floods. Over time, undocumented land-use change (deforestation, destruction/construction of levees/dams) alter the run-off and river flow characteristics, considerably complicating any analysis even if historical data were available. Each parameter or data set introduced into these models adds some uncertainty to it (Fistikoglu, 2002), potentially resulting in extreme over/under estimations due to the inadequate quality of the data.

Most hydraulic models are reliant on inflow data that are extracted from either gauge-station data or from run-off data processed by a hydrologic model. However, as base data sets for the hydrologic models are inaccurate and sparsely distributed in some developing nations, due to being out of necessity over extrapolated data sets, the results are unlikely to provide a high level of accuracy. The outcome is commonly a model that has the characteristics of a Rube Goldberg machine, where a very complex methodology is chosen to achieve a simple task, namely creating a basic medium-scale inundation map.

1.2. Solution based on observed past floods

What is proposed instead is to move away from models that are based on complete yet inadequate data sets, and focus on a parsimonious model that relies on available data, similar to parsimonious watershed modelling (Andréassian et al., 2002; Fistikoglu, 2002). A new KISS (Keep It Simple and Straightforward) method does provide a solution for flood hazard mapping where extracting the extreme flood extent is the primary goal and not the flood depth or frequency.

To create a medium or small-scale map, the inflow data can be determined by extracting flood depths from observed past floods. This past flood data can either originate from observed floods from aerial and satellite imagery (Sanyal and Lu, 2004, 2005), visible flood outlines in such imagery, accurate governmental reports, or the Dartmouth Flood Observatory (DFO) past flood database. The past flood data can be interpolated to feed a hydraulic model, which results in an inundation outline and maximum flood depth map.

This “reverse engineering” approach has not been utilised before in nationwide flood hazard map studies. Using this method based on past floods, the authors successfully deployed a nation-wide Flood Hazard Map of Afghanistan (AFG-FHM) at a scale of maximum 1:100,000 (Shroder et al., 2008) using a high-resolution DEM (digital elevation model), high-resolution satellite imagery and DFO past flood data.

1.2.1. Traditional model based on inflow rates

Traditional flood models are reliant on inflow data extracted from a hydrologic model that utilises precipitation, snow melt, temperature, run-off data and gauge-station data. These data are fed into a hydraulic model that relies on an accurate DEM, a river network and river cross-section profiles, but often incorporates evaporation, infiltration and Manning’s n values as well. All these data are combined in a feed-forward model to create a flood hazard map where open channel equations such as the Gauckler–Manning–Strickler formula are utilised. Often the generated flood hazard map is subsequently validated against past flood observations (Pappenberger et al., 2007), and if discrepancies are found a feedback mechanism is added where some of the base parameters are adjusted until the results realistically match the observed past floods. Fig. 1 shows a simplified sketch of hydraulic inundation modelling.

1.2.2. Parsimonious model based on past floods

As much of the data required in traditional hydraulic modelling are not available in LDCs and some developing countries, derived past flood data are utilised to set the inflow volume as an adjusted past flood inundation depth (see Section 2.3). The data can be combined with variable or fixed roughness coefficient values. Together with a hydro DEM and river network the data can be integrated in a Gauckler–Manning–Strickler equation to calculate the inundation extent. A validation procedure assesses if the modelled inundation extent matches the past flood extents. Fig. 2 shows a simplified sketch of the parsimonious model based on past flooding that was used to create the AFG-FHM.

2. Input data generation and hydrologic modelling

For the creation of the AFG-FHM, hydrologic modelling was not used in the traditional run-off model sense, where it is used to calculate discharge volume based on rainfall and snow-melt data, infiltration and evaporation rates. These data are not available for Afghanistan in sufficient accuracy to capture extreme flood events and it was not necessary in the scope of the study for the hydraulic model (see Section 3) to function properly. The term “hydrologic model” was used as most of the steps and derived products that are utilised traditionally in hydrologic modelling are also used to create the input data for the hydraulic model; data such as a hydrologically correct DEM and a river-line network.

2.1. Hydrologically correct DEM

The hydrologic modelling commences with correcting the raw high-resolution DEM data into a usable format for the hydrological process, resulting in a hydrologically correct DEM (hydro DEM). The
hydro DEM influences the inundation outline’s accuracy most profoundly, as data such as the flow direction, flow accumulation and river network are derived from it. For the creation of the AFG-FHM, natural depressions had to be taken into account; these represent endorheic (inland) basins with no outlet. Also, many spurious sinks existed, commonly caused by random and mostly small deviations in the elevation surface (Lehner et al., 2006). Limitations in massive-grid DEM processing hindered the development of the most optimum DEM used for AFG-FHM study, in particular the correction of sinks proved difficult. The high-resolution DEM had similar characteristics as the 1–3 arc second (30–90 m resolution) SRTM (Shuttle Radar Topography Mission) data, yet does not exhibit no-data cells.

The DEM’s hydrological correction methods rely on removal of sink anomalies by a filling, such as the Jenson and Domingue (1988) conventional fill-sink approach. These anomalies either originate from the sensor, processing of the DEM, or due to spatially large vertical changes. The fill-sink method is for many regions sufficient. However, in mountainous areas narrow gorges can merge and form obstacles with extreme elevation differences (>50 m). In these regions, the fill-sink method can result in wide-flat surfaces of 20 km long including branching of valleys. In subsequent river creation procedures, the extracted river is generally located on the valley side as many algorithms chose a shortest route in the absence of elevation differences (Jenson and Domingue, 1988; Tarboton et al., 1991). If these extracted rivers are utilised they can be hundreds of meters parallel to the actual river location and at a much higher elevation. This also affects the flood model, resulting in inundation areas with exaggerated depth (e.g. >25 m).

Therefore, a breaching or burn-in method is preferable for mountainous regions, to avoid the generation of large flat uniform surfaces. Breaching is an alternative to filling the DEM depression, by removing the obstruction that hinders downward flow. There are various algorithms which are capable of doing this quite effectively; John Lindsay’s Terrain Analysis System employs a wide range of breaching methods such as Rieger’s regular breaching method (Rieger, 1998) and the constrained breaching method of Martz and Garbrecht (1998). Unfortunately for this research study, no program was capable of doing this for the large basins of Afghanistan. Some promising products were out of scope because of the complexity and costs involved (e.g. CatchmentSIM, FAUCET).

For the AFG-FHM, a combination of fill-sink and manual breach methods were chosen. After an initial fill-sink version of the flood map, all areas which exhibited very unlikely deep floods (>7 m) were investigated to determine if they were caused by an incorrect location of the river centreline and obstruction in the DEM. In such cases, the obstruction area was manually breached. More than 2000 river lines were digitised over the obstacles, which were subsequently burned in the DEM. The lowest cell value of the DEM was assigned to replace all higher values. This method was overall quite successful, though some small errors still persist which had a limited effect on the flood outline.

2.2. River line and river width

After the creation of the hydro DEM, flow direction and flow accumulation grids were created using Archydro to extract the river locations. For the AFG-FHM river network creation, cells were attributed to be part of a river by setting a flow accumulation threshold of 10 km². This threshold could not be determined by the established method of Tarboton et al. (1991) due to time and computational limitations, instead the various threshold outputs were compared to high-resolution satellite imagery. The river network was subsequently converted to a three-dimensional river network where each vertex point was assigned the elevation height of the DEM.

The river network created for the AFG-FHM study was compared with other existing vector river networks available on Afghanistan, such as the Afghanistan Information Management Service (AIMS) river network and the USGS-L2-Streams created as part of the USGS Helmand Flood Hazard project (Pervez et al., 2006). The assessment was done overlaying all different vector networks on high-resolution satellite imagery and measuring the deviation from the actual river location. The assessment highlighted that the AFG-FHM river network is more accurate than any available public accessible river network (see Table 1); this is mainly attributed to the quality of the high-resolution DEM.

River width was an input requirement for Lisflood FP, a two-dimensional hydrodynamic model (Bates and De Roo, 2000), which was one of the models used to evaluate the AFG-FHM. Although not an input requirement for the hydraulic model, river width was a significant regression variable to set the inundation depth (see Section 3).

The river width was extrapolated from 308 river width measurement samples across Afghanistan using high-resolution satellite imagery. The river samples were selected for each type of Strahler stream order, and distributed across different basins. The samples were measured as far as possible downstream of a river and on straight stretches of river for consistency. A simple generalised linear model regression analysis was used to calculate the river width (Kratzera et al., 2006).

In general, hydraulic inundation models require a continuously inclined river in the flow direction. Flood models either generate faulty data or stop working altogether when the river is not continuously downward flowing (Bates and De Roo, 2000). The

<table>
<thead>
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<th>Table 1</th>
<th>River network comparison.</th>
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<td></td>
<td>AIMS</td>
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<tr>
<td>Minimum flow accumulation</td>
<td>–</td>
</tr>
<tr>
<td>Number of rivers</td>
<td>4950</td>
</tr>
<tr>
<td>Total length</td>
<td>41300 km</td>
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<tr>
<td>Mean distance to rivera</td>
<td>190 m</td>
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a Distance to actual river collected from 160 sample measurements in high-resolution satellite imagery. Extreme deviations or rivers that were digitised wrongly were ignored in this value.
model is quite stable if the flow paths go upward. This has the advantage that it is not necessary to use a perfect hydro DEM. Although a generated hydro DEM was available, tests showed that using it would generate many unrealistically wide-flat inundation areas. A DEM that was only partially corrected showed more realistic inundation variations true to the terrain. It must be noted that some unintentional backflow can be caused as a result.

2.3. Extraction of Dartmouth Flood Observatory data

The inflow or river height data for the hydraulic model was extracted from reference data of the Dartmouth Flood Observatory (DFO) Past Flood Database as well as from visually confirmed flood zones in high-resolution satellite imagery. The DFO detects, maps, and measures major flood events world-wide using satellite remote sensing. They record inundation events in the World Atlas of Flooded Lands. Furthermore, an Active Archive of Large Floods, 1985 to present, describes these events individually (Brakenridge et al., 2005). The DFO assumes that with an archive of reliable data, it will become increasingly possible to predict where and when major flooding will occur and to analyse trends (Brakenridge et al., 2005). The DFO data are captured by MODIS (Moderate Resolution Imaging Spectroradiometer) sensors aboard the Terra and Aqua satellites. The visible and near-infra red bands, with a resolution of 250 m, provide excellent water/land discrimination (Brakenridge and Anderson, 2006).

The inflow data of the model were matched with the highest recorded DFO inundation depth by combining the flood outline with the available high-resolution DEM. Although the MODIS satellites offer a multiple times per day coverage, it must be noted that the DFO data provide only a “flood” snapshot, for which it is unknown whether it is taken at the maximum extent of the floods or when the flood was already receding or still unfolding (see Fig. 3).

It was not possible to automatically extract the lowest point of the DFO data, assumed to be the river-line centre and the highest elevated DFO inundated point from the high-resolution DEM data. Because some of the DFO flood areas are so large, the floodplain gradient influences the inundation depth. Furthermore, the resolution of the MODIS sensor of past flood observations also affects the lowest and highest point, so these can be off-centre by a few hundred metres, generally <500 m (see Fig. 4).

The maximum inundation depth of a DFO flood area is calculated by subtracting the lowest measured point from the highest inundation point. The lowest point is the middle of the river cross-section that can be extracted from the three-dimensional river-line vertex points. The highest measured elevation point of the DFO data lies mostly at the fringe of the flood. Often, an alternative highest point needs to be chosen manually from high-resolution satellite imagery, to avoid using peak elevation points stemming from potential DEM errors or from the MODIS data resolution.

For the inundation model to function properly, it is imperative that river depths are extracted from the utilised DEM and not from potentially more accurate in-situ measured points; this can lead to overestimation of the extracted flood depth for small rivers. For wider rivers (e.g. +45 m) the high-resolution DEM will be able to differentiate between various rivers depths. However, for narrow rivers the DEM resolution will actually result in less flood depth, as it will average the elevation of the surrounding terrain.

In Afghanistan, the DFO recorded 24 major inundation events between 2002 and 2006, which had in total 3416 individual flood polygons which covered an area of 9500 km² of land excluding all large perennial lakes (e.g. Hamun Lake) or 19,000 km² including lakes. This area also includes many river beds and as such cannot be counted as all flood areas. Many of the flood events partially overlapped each other and all the individual polygons were merged into a single feature object that was subsequently subjected to a split/explode procedure into 1981 non-overlapping polygons. This generated at times very large continuous flood areas along river stretches (>50 km). All 1981 past flood observations were categorised and attributed to the river it covered. Around 5514 km² unique inundation areas have been covered or 10,300 km² including perennial lakes and river beds, but not multiple flood observations of the same area.

The observations in the 4-year timeframe do provide a good insight into the potential flood hazard and can provide a basis for extracting inundation depths. Of the 1981 unique past flood observation areas, 25% had an elevation difference of less than 4 m between the deepest and highest area. These values were quite realistic and were visually confirmed using high-resolution satellite imagery. It was not necessary to extract the depth values of all the other 75% values manually. Overall areas along the same river stretch had the same inundation depth, and flood areas within the same basin and on the same river category were also very similar in inundation depth value. A total of 415 individual inundation points were measured, compared and attributed to the 5 main basins.

3. Hydraulic modelling

Hydraulic modelling can be thought of as a dynamic process, which simulates where water will flow. Simply put, a certain amount of water is poured over the terrain and for each cell it is calculated where the water will flow to over a certain amount of time. It is a very computationally intensive process, as for each cell that has water in it, calculations are needed to know where it will flow to next, and this process needs to be iterated for each time-step over multiple hours.

In traditional feed-forward inundation models the river is generally void of water and water is added at the model edge or at inflow points, letting the water propagate within the river,
e.g. Lisflood FP (Bates and De Roo, 2000), HEC-RAS or MIKE Flood. For short river stretches this approach is possible, but for very large basins it can take days for the water of the inflow point to reach the model’s outlet boundary. Therefore in this parsimonious model the entire stretch of river had the same river depth value assigned to it, an adjusted factor of the inundation depth.

In the model a cell of the drainage network grid holds a certain amount of water, which is defined by the DEM’s resolution and flow depth. It then calculates what would happen with that water under the assumption that the river depth would be constant at that level for a certain amount of time. Although the water levels can vary spatially per river stretch, they remain constant during the simulation process (Assmann, 2003). All river cells belonging to the same river section (between branching and merging) have the same water level assigned to them. In theory it would be possible to utilise hydrograph inflow data as well, if available. Unfortunately, in Afghanistan these data were not available nor would it be feasible to compute all the hydrographs for such a vast area.

### 3.1. Calculation method

The flow velocity was calculated using the Gauckler–Manning–Strickler formula, which is utilised by many flood models. More advanced calculation methods exist such as the St. Venant, Navier–Stokes and adjusted Manning’s equations, yet they either require too many computational resources or do not function at the scale of interest. The Gauckler–Mannning–Strickler formula is a widely used method to calculate open channel flow (Gauckler, 1867):

\[ V = \frac{k}{n} \cdot R_h^{\frac{2}{3}} \cdot S^{\frac{1}{2}} \]

where:

- \( V \) is the cross-sectional average velocity (m s\(^{-1}\))
- \( k \) is a conversion constant equal to 1.0 for the metric system
- \( n \) is the Manning coefficient of roughness. The AFG-FHM uses a value of 0.036 based upon Pervez et al. (2006), and tests revealed that a variable value has little influence
- \( R_h \) is the hydraulic radius (m), which was the equivalent to the channel depth
- \( S \) is the slope of the water surface m/m

The flow propagation of inundation areas is based upon a hydrodynamic approach developed by Assmann (2003) (see Fig. 5). In this model, all eight neighbours of a raster cell are
considered; the discharge volume to the neighbouring cells is calculated using the Gauckler–Manning–Strickler formula; the gradient is defined by the difference between the lowest water level and the highest terrain elevation found in the cell and the neighbouring cells; this is done for each of the neighbouring cells; the width of the flow between cells is considered to be the same for all neighbours; though for the diagonal neighbour cells the algorithm accounts for the different length; the calculation is based on a virtual raster consisting of octagons, which have the same perimeter as the original raster.

The hydrodynamic approach of Assmann (2003) is a simplified two-dimensional hydraulic model in which no impulse transfer takes place. The simplifications mainly affect the open channel hydraulics, which can be described only roughly with the available parameters such as the resolution of the elevation model in the channel and the absence of cross-sections.

3.2. Continuous flow discharge model

The hydraulic model uses a Gauckler–Manning–Strickler equation. This implies that on areas with an increased gradient there will be less chance of inundation due to an increase of flow velocity, whereas on flat areas the chance of floodplain inundation increases. The parsimonious flood map model uses flood depth as a predefined variable for inundation instead of discharge volume. It would, however, be wrong to assume that all areas are inundated only based on the flood depth of the river nearest to it. Fig. 6 shows how the flood model works in relation to the pre-assigned flood depth. River cross-sections A through D are identical and have an identical flood depth, while cross-section E has a more narrow profile. In the river elevation profile (see Fig. 6), areas A and C have a steeper slope, where gravity is forcing the water to flow downstream. The “Inundation Extent Top view” shows that the inundation along areas A and C are less profound.

River cross-sections B and D do experience wide inundation areas due to a lower slope. The water flows not only downstream, but also propagates into the wider floodplain. Areas B and D also receive additional inflow from the steeper areas upstream, see arrows (A and C respectively).

River cross-section E is an exception. It is located on a very narrow stretch of river, which creates channel restrictions for water upstream.

Fig. 5. Flow propagation (after Assmann, 2003).

Fig. 6. Inundation model.
(D), potentially creating backwater flooding. This backwater flooding can additionally increase the inundation depth of D, expanding the inundation extent even further. Because the DEM is not fully hydrologically corrected, backflow can occur in uncorrected areas.

3.3. Inundation process

The modelling approach utilises a dynamic time-step approach similar to the Lisflood FP (Bates and De Roo, 2000), which improves computation time considerably. The time-steps calculate where water will flow from one time-step to the next, although it can be assumed that the model calculates where every droplet of water will flow for a specified period of time. In the AFG-FHM study the model calculates the flow of water for a period of 6 h.

Fig. 7 shows a very simplified overview of this process. In this sample, there is no additional upstream inflow nor is there outflow downstream, resulting in a gradual filling of the river cross-section.

The pre-processing time-step (0) shows the river with a pre-defined inundation depth (6 m) and width (30 m). In time-step (1), it will calculate where the water can flow to, thus expanding the inundation area and emptying the inundation source (pre-defined inundation depth). This results in a centre cell with a depth of 3 m, with 2 m depth value cells on the side.

In the second time-step (2), the model refills the inundation source, and calculates where the additional water will flow to, as well as calculating where the water will flow from the already inundated areas (2 m depth areas). In time-step (3), the inundation area has expanded. The elevation is a bit higher on the left, resulting in less depth as on the right expansion. Similar to time-step (2), time-step (4) calculates where all the water will flow to. In time-step (5), it is apparent that the water could not expand horizontally, thus the water depth increases. In subsequent time-steps the entire elevation will be flooded, as in this example only water is added and none is removed.

3.4. Calculation of flood depth

The inundation depth from past flood observations was calculated using a GML regression analysis. The extracted DFO inundation height values were used as dependent variables to predict the flood depth using the independent variables: river width, basin size, Strahler-order and Shreve-order. The inundation depth was subsequently put into the hydraulic model and adjusted to match the past flood outline. After this heuristic approach, a basin adjustment factor was added to account for the inundation depth variations between the different basins. Geomorphology has much influence on the discharge in a catchment and there are multiple methods available to calculate river basin geometry, such as Shape index (Si), Gravelius index (GI) and circularity ratio (RC), and the Elongation ratio (Re) (Binjolkar and Keshari, 2007). An inclusion of one of these factors in this regression analysis could have improved the determination of the flood more accurately. However, there was no method available to extract all the necessary variables, for instance it was problematic to extract the main stem upstream length for each individual river stretch. Additional independent variables such as snow cover or land-use can also be included to improve results. However, the choice of regression analysis must be adapted depending on which variables are selected.

3.5. Discharge volume less critical for AFG-FHM

For most hydraulic models accurate discharge volume is either extrapolated from gauge-station measurements or calculated from hydrological models, and forms a crucial input parameter. As this information is not available with sufficient accuracy for Afghanistan, adjusted flood depth as an inflow parameter was utilised instead. Generally it can be assumed that by using flood depth alone and not discharge volume, the model’s results would become less accurate overall. However, while trying to establish the extent of extreme flood events, the discharge volume is in fact less critical. If the inundation extent at the fringes of the AFG-FHM deviates 30 or even 150 m for large wide inundation areas, it will have little effect on the overall accuracy due to the scale of the study. The prime purpose of the AFG-FHM study was to capture maximum inundation extent, not flood depth. As it is a rather unconventional approach to utilise flood depth instead of accurate discharge data/river flow data, Fig. 8 exemplifies the limited influence of a 5-fold increase of discharge on the inundation extent.

As the intent is to capture extreme floods, there are underlining assumptions:

- The inundation area should include areas covered by previous floods such as the DFO, and by well defined markings in high-resolution satellite imagery
- The inundation area should not go beyond the floodplain
- It is not the intention to cover the entire floodplain
- The inundation area should always cover the river bed

Fig. 8 is based on data captured in Afghanistan: it shows a wide floodplain (1500 m) with a wide river bed (230 m) and a 60 m wide river. This is a typical scenario for a large flood, and it occurs in an agricultural area of Afghanistan. Two small natural levees have been formed at the fringes of the riverbed as well. These natural levees are a result of receding flooding with a decreased velocity that deposited material at the riverbed fringes. The flood depth for the AFG-FHM was set at 1.38 m above the river, resulting in an inundation area similar to “Inundation C”. Higher flood depths would not have altered the inundation extent substantially.

A 100 year flood area has also been indicated in Fig. 8, although in reality it might be less or more wide. The 100 year flood event will most likely have an extent located between inundation A and C. The flood extent has increased between 5% (A to B) and 12% (A to C) respectively. This is a relatively small increase of width, for such a wide flood area. In this model, this would imply a 3-pixel increase of flood width between inundation A and C. Without ground observations in Afghanistan, it is not straightforward to assess which inundation extent is more correct. It must be noted that an inundation depth increase of 2 m between inundation A and C is quite considerable.
4. Results

The AFG-FHM covers entire Afghanistan, an area of 650,000 km². The inundation outline was calculated along 51,700 rivers with a total length of more than 252,000 km. Only rivers with more than 10 km² flow accumulation were considered. The resolution of the GRID output image is 30 m; additionally 3 vector inundation outlines were created (>0.29 m, >1.21 m, >2.71 m

<table>
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<tr>
<th>Flood</th>
<th>Cross-sectional area</th>
<th>Average flood depth</th>
<th>Manning’s n</th>
<th>Width</th>
<th>Velocity</th>
<th>Discharge</th>
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<tr>
<td>A</td>
<td>3900 m²</td>
<td>3 m</td>
<td>0.036</td>
<td>1400 m</td>
<td>0.61 m·s⁻¹</td>
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<tr>
<td>B</td>
<td>2800 m²</td>
<td>2 m</td>
<td>0.036</td>
<td>1330 m</td>
<td>0.51 m·s⁻¹</td>
<td>1428 m³·s⁻¹</td>
</tr>
<tr>
<td>C</td>
<td>1400 m²</td>
<td>1 m</td>
<td>0.036</td>
<td>1250 m</td>
<td>0.33 m·s⁻¹</td>
<td>468 m³·s⁻¹</td>
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Fig. 8. Discharge volume in relation to inundation extent.

Fig. 9. (a,b) Aerial image with Grid image overlay of the AFG-FHM. (a) An aerial image of Kunar River in the Eastern part of Afghanistan; the area seen is approximately 5 by 2 km. (b) The same area overlaid with AFG-FHM Grid image. Maximum inundation depth 8.7 m in river centre line, minimum depth 0.01 m, maximum inundation width 774 m. The AFG-FHM is available for download from www.cimicweb.org, see Acknowledgements and limitations for more information.
5. Conclusion

A parsimonious flood hazard map model based on past inundation extents can successfully be applied in developing countries provided that a DEM with a minimum resolution of 90 m is available and sufficient past flood observation or if the flood depth can be extracted from high-resolution satellite imagery. A few years of flood observations will suffice to create a rudimentary flood maps: the data sets used for the creation of the Afghanistan Flood Hazard Map spanned 5 years. The Dartmouth Flood Observatory has collected global past flood events over the past 10 years and keeps expanding this data set, which will enable improvements of future of flood maps based on past flood extents.

The inundation model based on past floods is stable and it is not essential to include variable Manning’s n values. Although inclusion of variable Manning’s n values might yield better results in theory, tests revealed that these improvements are hardly noticeable for a medium-scale flood map. The reason for this is not straightforward. This could be the result of either that in the attempt to capture extreme flood events the medium map scale could be a factor, or because the past flood method already stabilizes the underlying hydraulic model. Wilson and Atkinson (2003, p. 1581) have also made similar observations stating “spatially distributed friction has a small effect on the flood wave when compared to the underlying elevation data”.

The model accuracy is primarily dependent on DEM resolution and not on the inflow rate. For extreme flood extent, mapping the inflow data has limited influence at a mapping scale of 1:100,000. The correct regression method and basin adjustment factor influences the outcome of the model more profoundly; validating and adjusting these data are an essential step, especially when working with different types of DEM and topographical areas.

For large-area flood mapping, computational resources play an important role in making modelling decisions. The Afghanistan Flood Hazard Map needed 2.5 months of pure hydraulic processing time on multiple high-end workstations. Additional processing time is needed to correct the DEM, and extract rivers and additional parameters.

By utilising a parsimonious model there will be limitations on the output accuracy, yet the Afghanistan Flood Hazard Map highlighted that such simplified models are a valuable alternative for developing countries where no accurate input data are available.

Acknowledgments and limitations

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References


Sanyal, J., Lu, X., 2004. Application of variable Manning’s n values. Although inclusion of variable Manning’s n values might yield better results in theory, tests revealed that these improvements are hardly noticeable for a medium-scale flood map. The reason for this is not straightforward. This could be the result of either that in the attempt to capture extreme flood events the medium map scale could be a factor, or because the past flood method already stabilizes the underlying hydraulic model. Wilson and Atkinson (2003, p. 1581) have also made similar observations stating “spatially distributed friction has a small effect on the flood wave when compared to the underlying elevation data”.

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