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Modelling of flood hazard extent in data sparse areas: a case study of the Oti River basin, West Africa

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ARTICLE INFO

ABSTRACT

Study region: Terrain and hydrological data are scarce in many African countries. The coarse spatial resolution of freely available Shuttle Radar Topographic Mission elevation data and the absence of flow gauges on flood-prone reaches, such as the Oti River studied here, make flood inundation modelling challenging in West Africa.

Study focus: A flood modelling approach is developed here to simulate flood extent in data scarce regions. The methodology is based on a calibrated, distributed hydrological model for the whole basin to simulate the input discharges for a hydraulic model which is used to predict the flood extent for a 140 km reach of the Oti River.

New hydrological insight for the region: Good hydrological model calibration (Nash Sutcliffe coefficient: 0.87) and validation (Nash Sutcliffe coefficient: 0.94) results demonstrate that even with coarse scale (5 km) input data, it is possible to simulate the discharge along this region's rivers, and importantly with a distributed model, derive model flows at any ungauged location within basin. With a lack of surveyed channel bathymetry, modelling the flood was only possible with a parametrized sub-grid hydraulic model. Flood model fit results relative to the observed 2007 flood extent and extensive sensitivity testing shows that this fit (64%) is likely to be as good as is possible for this region, given the coarseness of the terrain digital elevation model.

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1. Introduction

During the last two decades, many damaging floods have occurred in West Africa (Di Baldassarre et al., 2010). In September 2007, intense rainfall caused the worst floods this region had faced for many decades. The worst affected countries were Ghana, Burkina Faso and Togo with 56, 46 and 23 persons killed respectively (Tschakert et al., 2010). In order to improve the provision of flood hazard information in the study area and across West Africa generally, we require both hydrological and hydraulic models to first simulate the peak flows or high water level and then simulate inundation of this peak to identify flood-prone areas. Unfortunately, the lack of appropriate data availability (type and resolution) in the region prevents the application of standard engineering flood models. Recently, the research community have begun to tackle this challenge. For instance, when modelling flood inundation at the reach scale in data scarce environments, one of the difficulties is the coarse resolution of the freely available Digital Elevation Model (DEM) compared to the narrow width of the river channel. To tackle this issue, one solution developed by Neal et al. (2012) is to develop a sub-grid channel hydraulic model. Incorporated in the LISFLOOD-FP model, this approach provides a means of representing any river channel whose width is narrower than the spatial resolution of the topography data on low resolution terrain data where river geometry survey data are absent. This model was successfully validated for the Niger River in Mali (Neal et al., 2012). Other studies aiming at simulating flood inundation and propagation in a data sparse regions have also been carried out. Yan et al. (2014) use design floods derived from African envelope curves and a physical model chain to simulate flood extent with the LISFLOOD-FP model on the Blue Nile. The results of Yan et al. (2014) highlight the difficulties in modelling flood inundation extent in data scarce areas, particularly in generating realistic flood flows. Moreover, Sanyal et al. (2013) use the same raster-based hydrodynamic model (LISFLOOD-FP) to simulate flood inundation in a large ungauged river of the Damodar River in India. The authors highlighted the difficulties in performing hydrodynamic modelling in developing countries because of the lack of data but showed that even a few 'well-designed' field surveys can provide additional information to the free DEMs in order to improve flood routing. Although, the majority of these previous studies revealed the obstacles in modelling flood in developing countries, they do demonstrate the usefulness of the freely available DEM in accurately simulating flood dynamic in data scarce areas.

Given the absence of river geometry observations and the need to use globally available digital elevation data, the main objective of this study is to investigate the ability of the methods developed for data scarce areas to simulate the flood extent for the Oti River. This case study will further evaluate the sensitivity of inundation predictions to some key input variables that have not previously been examined in enough detail on the Oti River or elsewhere in Africa. Specifically, *(i)* how sensitive are the model results to the Manning's friction coefficient of the channel? *(ii)* How sensitive are the model results to river channel geometry parameters? And *(iii)* does changing floodplain DEM resolution have a substantial effect on water surface elevation and floodplain inundation simulation?

2. Study area and datasets

This study focuses on the Oti River basin which is a sub-basin of the Volta River basin of West Africa. In the present work, we consider approximately 140 km of the Oti River starting from the Mandouri gauging station (Fig. 1) and ending just downstream of Mango gauging station. Both gauges are currently abandoned.

The average width of the river in the study reach is 60 m and the model domain is between latitudes 10.20 and 10.84 degrees North and longitudes 0.02 and 1.15 degrees East. The study area is a rural catchment which is mainly characterized by agricultural land use with floodplain elevations from 103 m to 559 m over the model domain (Fig. 2a). The mean water level at Mango gauge station is about 5 m (Moniod et al., 1977).

In addition to the severe flood of 2007, the study area has experienced substantial events in the years 2010, 2008, 1999 and 1998. Further back in time, major floods also occurred in the Oti River basin on October 6, 1957 (10 m of water level at Mango gauge station) and September 21, 1962 with 10.64 m of water level at Mango (Moniod et al., 1977).
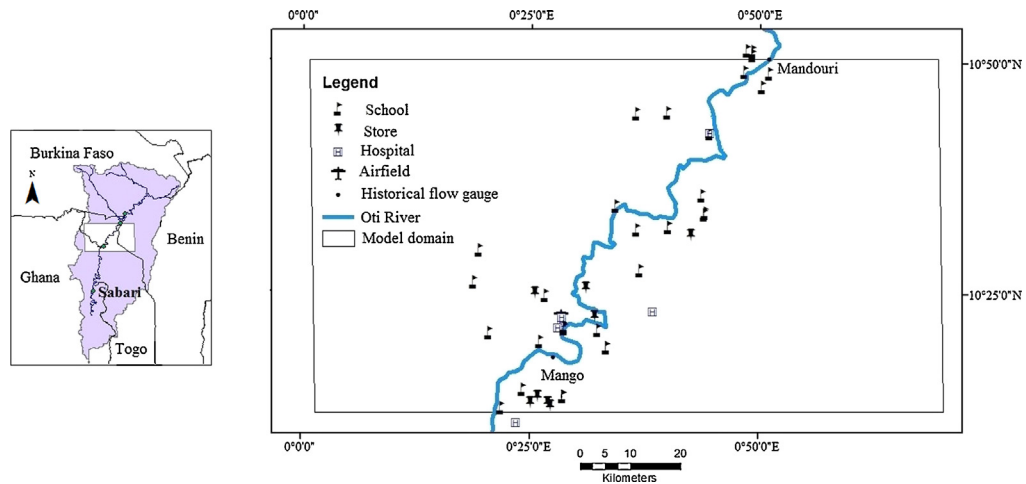
Fig. 1. Location of the study area showing the model domain, main settlements along the Oti River in Togo and historical flow gauges.
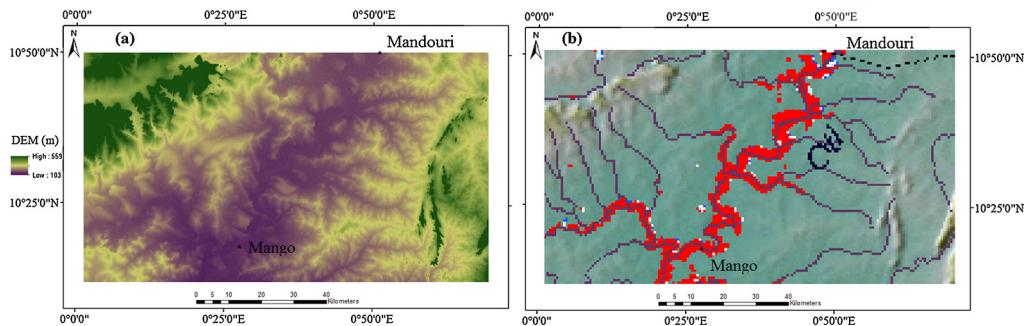

Fig. 2. (a) DEM of the study site from SRTM and (b) observed flood extent of the 2007 floods from NASA MODIS data (http://www.floodobservatory.colorado.edu) in red.

The extent of the 2007 flood was captured by NASA's[1] MODIS (moderate resolution imaging spectroradiometer) satellite and published by the Dartmouth Flood Observatory (Fig. 2b). However, observed discharge data for the study site are only available from the years 1959 to 1987 at Mandouri gauge station and from 1953 to 1989 at Mango gauge station, with many data gaps.

3. Methodology

To perform flood inundation modelling for the study area, two major steps were followed. First, calibration and validation of a distributed hydrological model (LISFLOOD) were undertaken, using remote sensing data and observed discharge data from downstream of our Togolese study site. Once complete, the model provided flow data for the 2007 event at our study site. Second, the LISFLOOD-FP hydraulic model (not to be confused with the hydrological model) was applied to the selected channel reach of the Oti River using the historical flood extent in 2007 for calibration.

3.1. Description of the hydrological model

The LISFLOOD hydrological model (version March 15, 2010) was used to simulate input hydrographs for the flood inundation modelling. LISFLOOD is a raster-based distributed hydrological model which was developed by the Joint Research Center of the European Commission (Van Der Knijff and De Roo, 2008). LISFLOOD hydrological model is implemented in the PCRaster modelling language wrapped in a Python based interface. The main components of this hydrological model are briefly described as follows: *(i)* a sub-model for the simulation of the water balance, *(ii)* sub-models for the simulation of groundwater and subsurface flow, *(iii)* a sub-model for the routing of surface runoff and *(iv)* a sub-model for the routing of channel flow. The model is mainly based on five calibration parameters namely: the upper zone time constant, lower zone

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[1] National aeronautics and space administration of United States of America.

Table 1
Remote sensing data used in the hydrological modelling.

Remote sensing data	Spatial resolution	Source
Tropical Rainfall Measuring Mission -daily rainfall	$0.25^0 \times 0.25^0$	http://iridl.ldeo.columbia.edu
Climate Research Unit - daily temperature (National Center for Atmospheric Research Staff, 2014)	$0.5^0 \times 0.5^0$	https://climatedataguide.ucar.edu/climate-data/cru-ts321
Harmonized World Soil Database -soil data	-	http://www.iiasa.ac.at/Research/LUC/luc07
Shuttle Radar Topographic Mission –elevation data	≈ 90 m	http://srtm.csi.cgiar
Satellite Application Facility-Leaf Area Index	3 km	http://Landsaf.meteo.pt
Land cover map	222 m $\times$ 222 m	http://131.220.109.2/geonetwork

time constant, ground water percolation value, power preferential flow and Xinanjiang parameter b (Van Der Knijff and De Roo, 2008).

3.2. Calibration and validation of the hydrological model

The rainfall-runoff model was applied at 5 km spatial resolution using the remoted sensing data that are shown in Table 1.
In order to reduce volume errors during the simulation, correction factors were estimated and applied to the daily gridded rainfall data. Due to the lack of sufficient climatological data, the reference evapotranspiration was computed using the Hargreaves and Samani equation (Hargreaves and Samani, 1985). Furthermore, the rainfall, mean temperature, leaf area index, reference evapotranspiration, potential evaporation from a bare soil and potential evaporation from open water were interpolated to 5 km spatial resolution using 'gstat' applications (Pebesma and Wesseling, 1998). Finally, the model was manually (trial and error method) calibrated for three years (2001, 2002 and 2003) and validated for three years (2005, 2006 and 2007) for Sabari gauge (catchment area:58, 670 km^2), downstream of the study area in the Oti River basin (Fig. 1). The performance of the hydrological model was assessed using Root Mean Square Error (RMSE) and Nash Sutcliffe coefficient NSE (Nash and Sutcliffe, 1970). Further details regarding the setup and calibration of the LISFLOOD hydrological model can be found in Van Der Knijff and De Roo (2008).

3.3. Description of the flood inundation model

In this study, LISFLOOD-FP version 6.0.4 (Bates et al., 2013) was used to model the floodplain extent of the Oti River. LISFLOOD-FP is a raster based hydraulic model developed at the University of Bristol. The hydraulic model solves numerically the local inertia (Neal et al., 2012), diffusive (Trigg et al., 2009) or kinematic (Bates and De Roo, 2000) approximations to the one-dimensional Saint-Venant equations in order to simulate the propagation of the flood wave through the river channel. In this model, the river channel is represented using the local inertia approximation implemented at sub-grid scale (Neal et al., 2012). The required data of channel widths were manually measured at 2 km intervals from Google maps along the channel centreline. Due to the lack of detailed river bathymetry, the cross-section of the river channel was modelled using a rectangular channel approximation.

The performance of LISFLOOD-FP to predict flood inundation extent has been widely tested using observed flood extent maps from satellite (Di Baldassarre et al., 2009). In addition, the model has given good results in flood inundation modelling not only in Europe (Bates et al., 2010) but also in West Africa (Neal et al., 2012), Southern Africa (Schumann et al., 2013) and North Africa (Yan et al., 2014) and the Amazon (Wilson et al., 2007, Baugh et al., 2013).

3.4. Application of the LISFLOOD-FP model

3.4.1. Model setup.

A coupled 1D-2D LISFLOOD-FP model was set up for a 140 km reach of the Oti River using the sub-grid solver as described by Neal et al. (2012). The sub-grid model was chosen for this study because of its ability to be applied in data scarce environment. The application of the sub-grid solver of LISFLOOD-FP requires the specification of the centerlines of the river, floodplain topography, river widths, river bank elevation, inflow hydrographs and downstream boundary conditions along with model friction and channel depth parameters. The centerlines were derived from the digital elevation model using the flow accumulation function in ArcMap software. Apart from the inflow hydrographs and the model friction parameters, all the input data were created in ArcMap software and projected in a Cartesian coordinate system (UTM zone 31 N). These raster data sets were exported as text files (asci raster) to be read by LISFLOOD-FP.

In addition, a DEM ($\approx$30 m horizontal resolution) of the study area was obtained from the SRTM (shuttle radar topographic mission) data set. No elevation correction for vegetation errors was made because the floodplain and the river banks of the Oti River are situated in a semi-arid region with a sparse savanna vegetation. Therefore, errors in the SRTM elevation values due to vegetation cover are not expected to be significant in this area (Baugh et al., 2013). Starting from the original 30 m resolution, five other raster grids (60 m, 120 m, 240 m, 480 m and 960 m) were created by aggregating mean values in order

to test the accuracy of the model at the different resolutions and assess the sensitivity of the model outputs to floodplain DEM resolution.

The river widths were measured from satellite imagery (Google earth) acquired in February 2015. In this period, it is easy to identify the channel width because the river is within its banks. Moreover, the river bank elevation was estimated from the DEM by extracting the elevation of the floodplain cells that are adjacent to the river and smoothing these along-river over a distance of 1 km using a moving window filter. A free boundary condition that specified that the valley slope and water surface slope were equivalent at the boundary was applied to the downstream end of the model to allow water to leave the model domain.

Since the study site is characterized by a lack of recent observed hydrological data, the LISFLOOD rainfall-runoff model (as described in Section 3.2) was used to simulate input discharge data. The hydrograph of the reach outlet was then used as the input at the upstream end of the model to ensure all lateral inflows over the reach were accounted for in the hydrodynamic modelling. However, it is important to note that alternative methods, namely remote sensing techniques, have been proposed to estimate daily discharge at ungauged sites of catchments (e.g. Bjerklie et al., 2005; Birkinshaw et al., 2014; Sichangi et al., 2016). The satellite altimetry typically provides stage data for rivers more than 100 m wide (Birkinshaw et al., 2014), making difficult the application of these techniques for rivers less than 100 m wide, such as the Oti River.

Finally, the sub-grid channel solver of LISFLOOD-FP has four parameters namely; the Manning's friction coefficient separately for channel and floodplain, and also the exponent (p), and coefficient (r) of the hydraulic geometry. Manning's friction coefficient is a parameter that characterizes flow resistance for both the river channel and the floodplain. Manning's friction coefficient can be distributed in space but the model is typically set up with one component for the floodplain (n_{fp}) and another component for the river channel (n_c) where only limited data for the river are available. According to Chow (1959), Manning's friction coefficient for channel varies from 0.03 (clean) to 0.1 (very weedy/rocky reaches) and Manning's friction coefficient for floodplain from 0.03 (pasture short grass) to 0.120 (heavy stands of timber and a few fallen trees). The hydraulic geometry coefficient affects the area and hydraulic radius of the channel bankfull cross-section (Neal et al., 2012) and can be estimated from hydraulic geometry relationships proposed by Leopold and Maddock (1953) and rearranged by Neal et al. (2012) to obtain the following expression shown in Eq. (1):

$$d = rw^p \tag{1}$$

Where d and w are the reach averaged depth and the reach averaged width respectively, whilst r and p are the hydraulic geometry parameters. Due to the lack of data in the study area, the initial values of the four parameters (p, r, n_{fp} and n_c) where obtained from Chow (1959) and Leopold and Maddock (1953).

3.4.2. Sensitivity tests.

Three sets of sensitivity tests were undertaken with the finished hydraulic model, sensitivity to; (*i*) channel friction, (*ii*) channel geometry, (*iii*) floodplain DEM resolution. Firstly, the aim of the channel friction simulations was to test the sensitivity of the model results to different values of Manning's friction coefficient of the channel (n_c) ranging from 0.02 to 0.05 in 0.001 increments. For each sensitivity test, the values of the other parameters were held constant. Other application of LISFLOOD-FP (e.g. Horritt, 2006; Di Baldassarre et al., 2009) have shown that the model sensitivity to the floodplain friction parameter is often negligible or at least much lower than the sensitivity to channel friction. Therefore, it will not be considered in this study. Secondly, the sensitivity of the flood inundation extent to the river channel geometry was tested by running the model for different values of the coefficient of the hydraulic geometry (r) ranging from 0.035 to 0.175, in 0.005 increments This is in effect a linear scaling of the channel depth, with reach averaged depth increasing with r. For each simulation, the values of the other parameters were set constant. Finally, to test floodplain DEM resolution, the model was run using the six different resolutions of the floodplain DEM outlined above.

3.4.3. Simulation of the 2007 flood event

We used the hydraulic model to simulate the extent of the 2007 flood event for a period between 1st May 2007 and 30 November 2007. The simulated inundation extent was compared with the MODIS (Fig. 2b) satellite observation, produced on September 21, 2007, using a simple index of fit measure F (Bates and De Roo, 2000). The F measure allows quantitative comparison of the simulated extent to the satellite observation. The performance measure (F) is given by Eq. 2:

$$F(\%) = \frac{A \cap B}{A \cup B} \times 100 \tag{2}$$

where A is the observed inundated area, and B the inundated area predicted by the model. In order to calculate F, an inundation boundary vector was first created from the observed satellite image, as the original MODIS raster analysis was not obtainable. The boundary vector was converted to a binary wet and dry raster, resampled to the same resolution as the model simulation output. The same wet and dry classification was applied to the simulation results. In order to calibrate the model, we consider only the Manning's friction coefficient for channel and the hydraulic geometry coefficient which were sampled in the range of the intervals given in Section 3.4.2 of this paper.
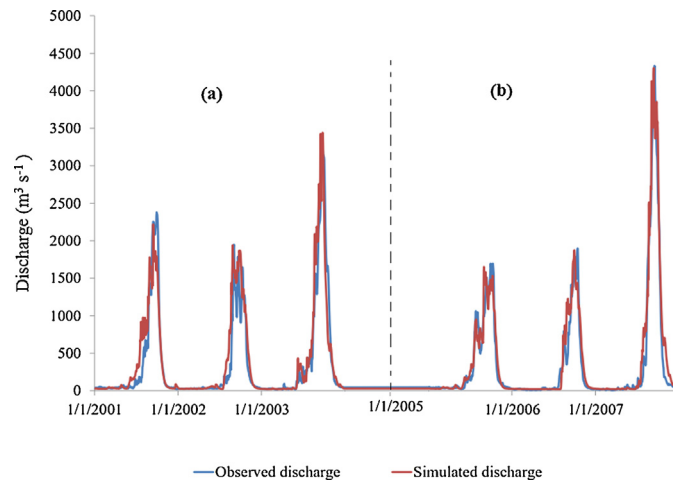
Fig. 3. Comparison between simulated and observed hydrographs at Sabari for the calibration (a) and validation (b).

4. Results and discussions

In this section we briefly present the results of the hydrological modelling, but we focus in detail on the results of the hydraulic modelling.

4.1. Hydrological modelling

The calibration of the hydrological model using data from 2001 to 2003 resulted in NSE and RMSE values of 0.87 and 237 m³/s while the model validation using data from 2005 to 2007 produced better performance measures (NSE = 0.94 and RMSE = 179 m³/s). The RMSE is 9% of the mean flood discharge for the calibration period and 0.7% for the validation period. Generally, the goodness-of-fit measures for calibration are better than for validation (e.g. Bormann and Diekkrüger, 2003; Ibrahim et al., 2015; Masafu et al., 2016) since the calibration process seeks to minimise differences between the observed and simulated time series. In this particular case, the goodness-of-fit measures are actually better for validation than calibration. This would suggest that variability from the norm in the calibration data set is greater than in the validation data set. Moreover, Fig. 3 shows the comparison between the simulated and observed hydrographs. These plots reveals that except for the year 2001, all the peak flows are well simulated by the hydrological model. This high performance of the LISFLOOD hydrological model helped to generate discharge data for the flood inundation modelling.

Finally, the best calibration parameters of the LISFLOOD hydrological model are tabulated in Table 2, with the lower and upper bounds suggested by Van Der Knijff and De Roo (2008). It is worth nothing that for all the calibration parameters, the best values lie within the ranges specified in Table 2.

In order to evaluate the contribution of lateral flows along the studied river reach, Fig. 4 shows the comparison between the simulated hydrographs at the inlet (Mandouri with an area of 29,100 km²) and outlet of the studied reach (Fig. 1). It can be noted that the peak discharge at the outlet of the studied reach is about 31% higher than the peak flow at the inlet. This increase of discharge from the upstream boundary to the downstream end suggests some contributions of lateral inflow, which has been taken into account in the hydraulic modelling.

4.2. Hydraulic modeling

4.2.1. Sensitivity analysis results.

The initial parameters of the model were obtained from Leopold and Maddock (1953) and Chow (1959) and are shown in Table 3. Fig. 5 shows the performance of the LISFLOOD-FP at 960 m DEM resolution with different Manning's friction coefficients for the channel (Fig. 5a) and with different values of the hydraulic geometry coefficient r (Fig. 5b). One can note

Table 2
Optimal values of the calibration parameters. The lower and upper bounds of the parameters were taken from Van Der Knijff and De Roo (2008).

Parameter	Optimal values	Lower bound	Upper bound
Upper zone time constant	10	1	50
Lower zone time constant	1300	50	5000
Ground water percolation value	0.1	0	1.5
Xinanjiang parameter b	0.3	0.1	1
Power preferential flow	2	1	6

that the performance of the sub-grid model peaked at n_c of 0.042 but decrease with further increase in the value of n_c. The model performance was less sensitive to Manning's n when the optimal n was exceeded. This behavior is commonly seen when large flood events are assessed using spatial performance measures because the flood extent tends to increase only gradually with increased water depth once most of the floodplain valley is inundated. The maximum performance measure for r was obtained at 0.04. From these results, it is clear that both the friction coefficient for the channel and the hydraulic geometry coefficient influence the inundation extent in this case study. However, the sensitivity of the model results to the hydraulic geometry coefficient was relatively low compared to friction coefficient for channel.

4.2.2. Effects of DEM resolution on the simulation results.

Water elevation along the river from the simulations results for the different aggregated DEM resolutions are shown in Fig. 6. The simulated water surface elevations are almost the same for the different aggregated DEM resolutions with a slight difference at about 80 km of the reach where the water surface elevations from 480m and 960m DEM resolution are over 1 m lower than the water surface elevations for 30m, 60m, 120 m and 240m DEM resolutions. Generally, by changing the resolution of the floodplain DEM, other inputs to the model namely channel width and bank elevation must be aggregated as the resolution coarsens. This can locally affect the channel slope and simulated water surface elevations along with the differing topographies (e.g. Dutta and Nakayama, 2008). However, the results of the present study show that the DEM resolution doesn't really affect the water surface elevation simulations in most locations, meaning that the changes in extent with resolution are essentially due to the detail of the DEM rather than any more complex hydraulic interaction between the DEM and river channel. The variation of the model performance in simulating the floodplain extent when the DEM resolution coarsens is presented in Table 4. This table shows that the performance of the model actually decreases with resolution and there could be a number of reasons for this. It might be that the local scale noise in the SRTM data is reducing the accuracy of the inundation simulation at finer resolution e.g. some smoothing of the DEM by aggregating to lower resolution might be beneficial for the flood extent simulation in this case. Another factor is the validation data resolution. The model performs
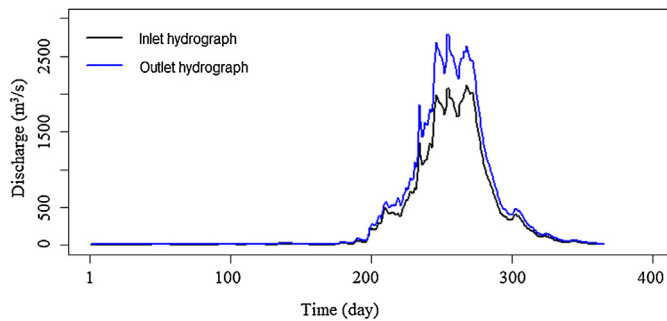

Fig. 4. Simulated hydrographs of the 2007 flood at inlet and outlet of the studied reach (see Fig. 1 for the model domain).

Table 3
Initial values of the hydraulic model (LISFLOOD-FP) parameters.

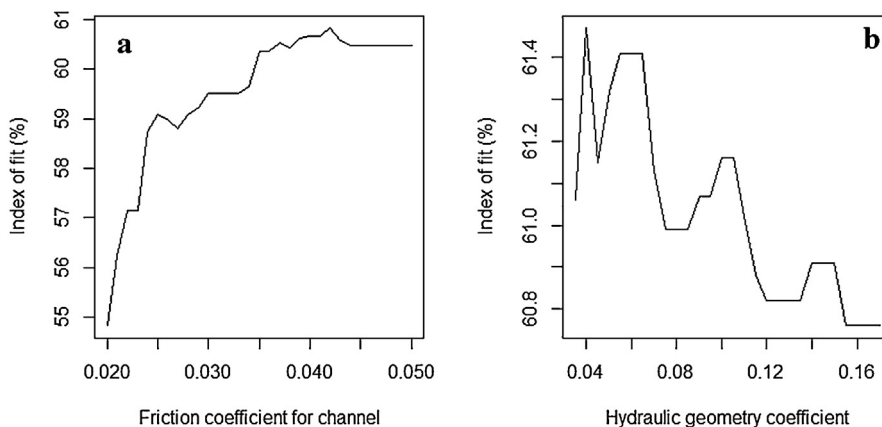| Parameters	n_c	n_{fp}	p	r
Initial values	0.03	0.04	0.74	0.36

Fig. 5. Performance of the sub-grid model of LISFLOOD-FP with (a) different Manning's friction coefficient for channel and with (b) different hydraulic geometry coefficient.
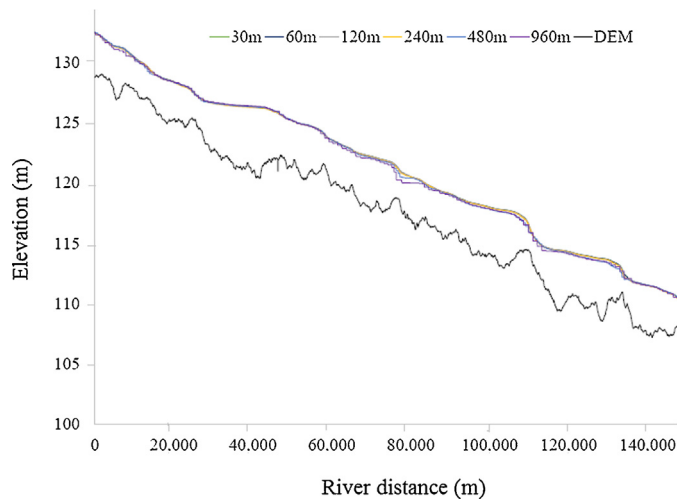
Fig. 6. River bed longitudinal profile (black line based 30 m DEM minus river depth) and water surface elevations simulated by LISFLOOD-FP for different aggregated DEM resolutions.

Table 4
Performance of the sub-grid model of LISFLOOD-FP for different DEM resolutions.

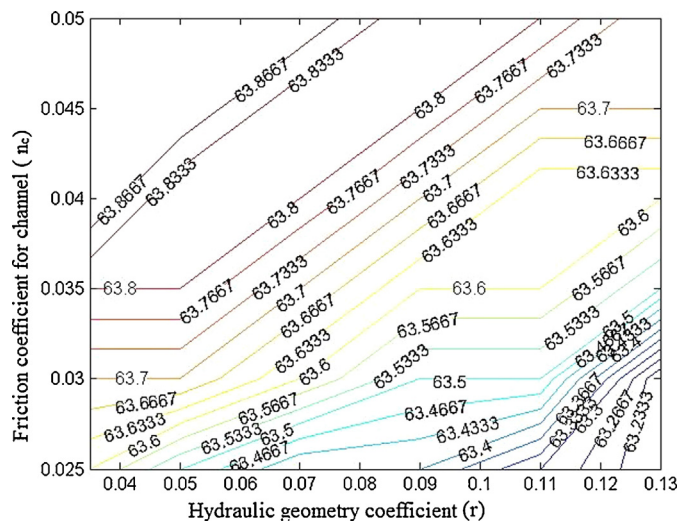| DEM resolutions (m)	30	60	120	240	480	960
Index of fit (%)	52	53	56	59	60	59

Fig. 7. Results of the calibration of the sub-grid model of LISFLOOD-FP showing measures of fit as a function of the hydraulic geometry coefficient and the Manning's friction coefficient for channel.

worse when you go to a higher resolution than that of the model validation data and this might be expected given that the validation data cannot represent the finer scale detail in the inundation model.

4.2.3. Simulation of the 2007 flood event

The optimum hydraulic model parameters are given in Table 5 while Fig. 7 shows the results of the calibration for the hydraulic model at 480 m DEM resolution as contour plots of measure of fit over the parameter range. The best fit of the sub-grid model of LISFLOOD-FP is characterized by a Manning's coefficient for channel (n_c) of around 0.045 $m^{1/3}S^{-1}$ and 0.05

Table 5
Models' parameters used for the flood inundation modeling.

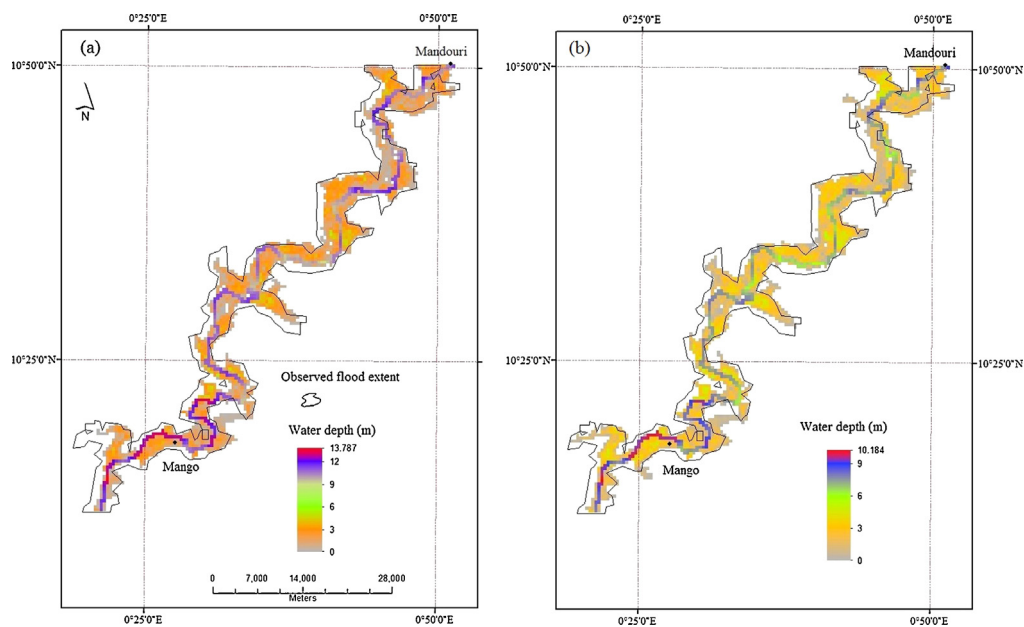| Parameters	n_c	n_{fp}	p	r
Optimum parameters	0.045	0.04	0.74	0.05

Fig. 8. Comparison of simulated flood extent with (a) satellite observation before calibration (b) and after calibration for the severe flood of September 2007.

for the coefficient of the hydraulic geometry (r). However, by analyzing Fig. 7, one can observe that different combinations of optimum parameter values may fit the calibration data equally. This equifinality in flood inundation modelling has been already illustrated in the scientific literature (e.g. Bates et al., 2005; Di Baldassarre, 2012).

It is interesting to note that a performance measure of 60% was achieved for the simulated flood extent prior to the calibration (Fig. 8a) compared to 64% after the calibration (Fig. 8b).

The values of F found for this study are relatively low compared to previous studies where either high resolution topography was available or the floodplain was many kilometers wide (e.g. Bates and De Roo, 2000; Horritt and Bates, 2001; Wilson et al., 2007) but relatively high compared to the results from other data sparse areas such as Amarnath et al. (2015) who found 38% for F and similar to the results of Sayama et al. (2012) who found 61% for F. However, the model simulation can be considered as an acceptable result because the majority of the flooded areas along the main reach was identified as shown visually in Fig. 8b and other studies have obtained similar fits when SRTM data has been used. The disagreements between the observed and simulated flood extents occur where the centrelines derived from the DEM by flow accumulation do not correspond with observed river channel locations. Moreover, some of the flooding occurred on tributaries that we have not included in the model.

4.3. Limitations

In this paper, a methodology to simulate flood extent on ungauged rivers is presented. This methodology links rainfall-runoff modelling and hydraulic modelling to delineate flood extent. A distributed hydrological model was initially used to generate the flood hydrographs of interest. This approach is useful to transfer hydrological information from gauged catchments to ungauged sites and simulate flood extents in flood prone-areas which suffer from lack of hydrological information. However, it is important to note that due to the lack of sufficient data to validate the hydraulic model, as well as the simulation characteristics, it is difficult to eliminate a certain degree of uncertainty. This uncertainty was not estimated in the present study because it is computationally expensive particularly for combined hydrologic and hydraulic simulations. Nevertheless, the sensitivity analyses performed in this work can be useful to understand both the simulation uncertainty and the behavior of the model with different parameter values and DEM resolutions (e.g. Sayama et al., 2012).

5. Conclusion

The main objective of this study is to explore a methodology for simulating flood extent in data scarce areas using a hydrological model (LISFLOOD) and flood inundation model (LISFLOOD-FP). The application of the hydrological model shows its good performance in predicting peak flows in the region of the Oti River basin (RMSE represents less than 10% of the mean peak flows).The simulated hydrograph of the severe flood of September 2007 is very close to the observation with 0.7% error for the peak flow, and was used to provide input hydrograph for the hydraulic model. Given the DEM data available and the similar fits obtained by other studies where STRM data have been used, the index of fit of 64% obtained

in this study is considered acceptable. The results of this study show also that in contrast to the simulated water surface elevations, the modelled flood extent is more sensitive to the grid resolution. In addition, the sub-grid model of LISFLOOD-FP showed more sensitivity to the Manning's friction coefficient for the channel than to the hydraulic geometry coefficient.

The possibility to identify and predict flood prone areas on ungauged rivers is the major advantage of the proposed methodology. It is the first time that a flood inundation modelling has been undertaken for the Oti River basin and the outcomes of this study can contribute towards an efficient flood risk management decisions for this area. For instance, flood inundation maps can help in mitigating flood damages and establishing early flood warning systems. Moreover, the calibrated models (hydrological and hydraulic) could be used to assess the future impacts of climate and land use changes on flood risk in the Oti River basin.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgments

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