International Conference on Hydroinformatics

2014

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Kun Yan

Florian Pappenberger

Yakob M. Umer

Dimitri P. Solomatine

Giuliano Di Baldassarre

11th International Conference on Hydroinformatics
HIC 2014, New York City, USA

REGIONAL VERSUS PHYSICALLY-BASED METHODS FOR FLOOD INUNDATION MODELLING IN DATA SCARCE AREAS: AN APPLICATION TO THE BLUE NILE

KUN YAN (1), FLORIAN PAPPENBERGER (2, 3), YAKOB M. UMER (1), DIMITRI P. SOLOMATINE (1, 4), GIULIANO DI BALDASSARRE (1, 5)
(1): Integrated Water Systems & Governance, UNESCO-IHE, Institute for Water Education, Westvest 7, Delft, 2611 AX, the Netherlands
(2): European Centre for Medium Range Weather Forecasts, Shinfield Park, Reading, RG2 9AX, UK
(3): College of Hydrology and Water Resources, Hohai University, No. 1 Xikang Road, Nanjing, China
(4): Water Resources Section, Delft University of Technology, Stevinweg 1, Delft, 2628 CN, the Netherlands
(5): Department of Earth Sciences, Program for Air, Water and Landscape Sciences, Uppsala University, Villav. 16, 75236 Uppsala, Sweden

Abstract

One of the main obstacles in mapping flood hazard in data scarce areas is the difficulty in estimating the design flood, i.e. river discharge corresponding to a given return period. This exercise can be carried out using regionalization techniques, which are based on flood data of regions with similar hydro-climatic conditions, or employing physically based model cascades. In this context, we compared the flood extents maps derived for a river reach of the Blue Nile following two alternative methods: i) regional envelope curve (REC), whereby design floods (e.g. 1-in-20 and 1-in-100 year flood peaks) are derived from African envelope curves and ii) physical model cascade (PMC), whereby design floods are calculated from the physical model chain of the European Centre for Medium-Range Weather Forecasts (ECMWF,). The two design flood estimates are then used as input of a 2D hydraulic model LISFLOOD-FP and the simulated flood extents are quantitatively evaluated by comparing to a reference flood extent model, which uses design floods estimated from in situ data. The results show the complexity in assessing flood hazard in data scarce area as PMC largely overestimates the flood extent, while REC underestimates it.

Key words: Flood hazard mapping, regional envelope curve, physical model cascade, design flood estimation, LISFLOOD-FP

INTRODUCTION

Strategies to cope with floods such as flood hazard mapping rely on effective prediction of flood extents from flood inundation models. One of the essential input data for flood inundation modelling is the hydrological input (e.g. design floods: river discharge corresponding to a given return period). The design floods are conventionally derived from the historical discharge records of a given catchment. However, these measurements are usually missing in many areas of the world where are effectively ungauged (Stokstad 1999).

Inundation modelling is therefore difficult to be implemented in data scarce areas due to the difficulties in design floods estimation. To tackle this issue, one of the attempts by Pappenberger et al., (2012) was to derive the discharge globally for different return periods using a large scale physical model cascade (PMC). It included the derivation of meteorological forcing data and discharge acquisition from a land surface model based on a 30 year (1979 - 2010) simulation period. A global flood hazard map was produced by feeding the derived discharges into a river routing model. After the evaluation with the bench mark data, the results indicated that the approach is feasible and can produce realistic global flood hazard maps of various return periods.

Alternatively, the use of empirical regional envelope curve (REC) of flood flows is a traditional approach to simulate extreme floods in ungauged basins (e.g. Castellarin, 2007). REC shares the concept of transferring the hydrological knowledge from gauged catchments to ungauged (or poorly gauged) catchments and provide an effective summary of regional flood experience (Padi et al., 2011). The estimated design floods are believed could be used to generate flood hazard maps across the globe, including in data-scarce areas.

Despite the proven feasibility of the two methods, there is a lack of quantitative evaluation of flood hazard maps produced based on them. The question therefore focuses on how robust these methods are for flood mapping, in particular, how accurate the estimated flood extents are based on the derived design floods. Thus, this study aimed at determining the appropriateness of the REC and PMC for deriving flood hazard maps in a large-scale data-scarce area.

Topography is anther essential input for inundation modelling. Among various products, high resolution, high accuracy topographic data (e.g. Light Detection and Ranging, LiDAR) are sometimes cost prohibitive, particularly in developing countries. On the other hand, freely available (or low cost) earth observation data have been released, such as the Shuttle Radar Topography Mission (SRTM). Even SRTM is termed as low-accuracy low-resolution topography, various efforts have proved the potential usefulness of SRTM topography on large scale flood studies (e.g. Sanders, 2007; Neal et al. 2012; Yan et al. 2013).

To this end, we compared the flood extent maps generated by a SRTM-based flood inundation model using design floods estimated through two methods: PMC and REC in this study. The two flood maps were benchmarked with the one derived by the same model utilizing design foods estimated from in situ data. The reliability and appropriateness of the two maps were quantitatively evaluated.

CASE STUDY: BLUE NILE

Test site and data availability

The Blue Nile and its tributaries rise on the Ethiopian plateau, stretch nearly 850 km between Lake Tana and the Sudanese-Ethiopian border with the average elevation of 2000 to 2600 m. The study was carried out on a river reach of Blue Nile around 280 km between Rosaries Dam and Sinnar Dam in Sudan, with a mild slope of about 0.12×10^{-3} (Figure 1). The historical discharge data is available at gauge station EI Deim near the Sudan-Ethiopia borders, which is about 70 km upstream of Rosaries Dam. These data provided by the Ministry of Water and Energy of Ethiopia are 25 years of annual maximum discharge cover the whole rainy season (from June to September) (Baratti et al., 2012). The topographic data of the test site is the SRTM Degital Elevation Model (DEM) with 90 m`s resolution. It was post-processed by the Consortium for Spatial Information of the Consultative Group for International Agricultural

Research (CGIAR-CSI), e.g. fills in the no-data holes in the raw SRTM data (Jarvis et al., 2008).

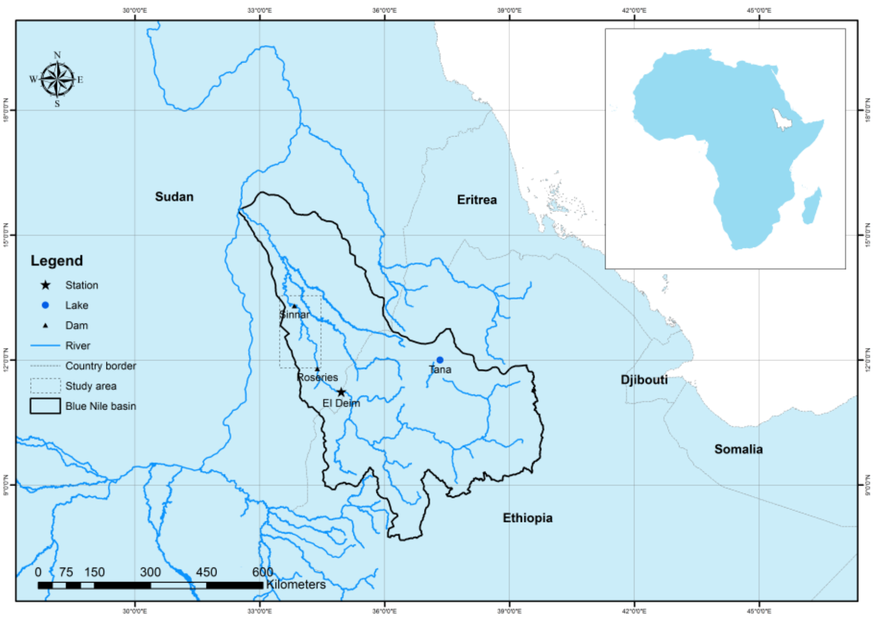

Figure 1Blue Nile basin and study area

Design flood estimation from ground data

The discharge data observed at EI Deim gauge station were used for the design flood estimation. The Gumbel (EV1) distribution function commonly used in extreme value analysis in hydrology was fitted to the annual maximum discharge series to derive the 1-in-100 and 1-in-20 year design flood (Table 1).

Design flood derived from REC

The design flood in ungauged basins can be derived using regionalization techniques (i.e. REC). Padi et al., (2011) analyzed African flood data and derived probabilistic regional envelope curves for the African continent. The flood experience in the African continent (Figure 2, right panels) was described by the equation:

$$\ln\left(\frac{Q}{A}\right) = a + b\ln(A) \qquad (1)$$

Where Q is the discharge and A is the drainage area, while a and b are the intercept and slope of the line. The specific discharge (i.e. Q/A) of a particular design flood (i.e. 1-in-100 year and 1-in-20 year) were calculated (Figure 2, left panels). The design floods of the study area were extrapolated from the line with the known catchment area.

Design flood derived from PMC

In this study, the European Centre for Medium Range Weather Forecasts (ECMWF) land surface model HTESSEL was coupled with ERA-Interim reanalysis meteorological forcing data to generate runoff for a 30 year (1979-2010) simulation period. The discharges were calculated by the physical model chain for a 25 km grid resolution. Similar to the design flood of ground data, the Gumbel (EV1) distribution function was fitted to the annual maximum discharge of 30 years to derive the design floods of the study area (Table 1).

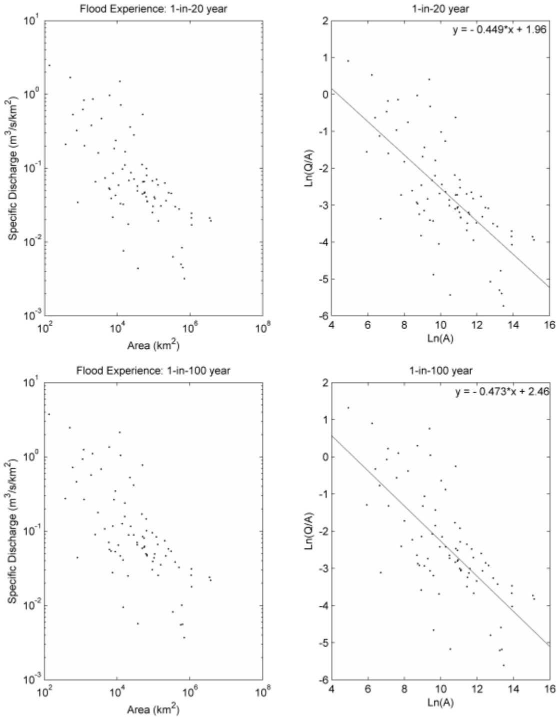

Figure 2 Flood experience (Right panels) and regional envelope curve of Blue Nile for two return periods (Left panels): Q/A in m^3/s/km^2 and A in km^2

Table 1 Design flood estimation with three methods: REC, MPC and In situ

Return Period	Design Floods Estimation (m3/s)		
	REC	PMC	In situ
1-in-20 year	5454	24109	10640
1-in-100 year	6799	28447	12621

HYDRAULIC MODELLING

The LISFLOOD-FP (Bates et al., 2010) two-dimensional (2D) hydraulic code solves simplified version of the shallow water equations that preserve acceleration but neglect advection term. The model provides the water depth and discharge for each time step in each cell based on the raster grid being used. It was largely used for floodplain inundation and has been proved to properly perform in numerous test sites (e.g. Neal et al 2012; Horritt and Bates, 2002). We therefore chose LISFLOOD-FP to simulate the flood extents as it provides a good compromise between physical realism and computational efficiency.

We set up LISFLOOD-FP models to propagate discharges derived by three methods (i.e. REC, PMC and In situ) for two return periods (i.e. 1-in-20 and 1-in-100 year). The topography input was the SRTM DEM with the resolution of 90 m. We assumed the discharges measured at EI Deim station as that of entering Rosaries reservoir due to the river reach between EI Deim station and Rosaries reservoir is quite stable with consistent river width. To avoid assuming the shape of the hydrographs, the steady state of design flood discharges were set as the upstream boundary conditions of the LISFLOOD-FP models. The simulation periods were set as long enough to ensure the maximum inundation extents were obtained for all simulations. The downstream boundary conditions were defined using the normal depth assumption. The water surface slope is estimated as the average bed slope under the assumption of a Manning's type relationship between water stage and discharge at the downstream end of the river reach. Given the water surface slopes were unknown, the average slope obtained from SRTM DEM for a reach of about 1000 m from the downstream end was employed as a downstream boundary condition for all simulations.

Due to the fact that the SRTM`s Interferometric Synthetic Aperture Radar (SAR) technology cannot detect channel geometry beneath water surface, the channel bed elevation is overall overestimated (Farr et al. 2007). The overestimated bed elevation could be partially compensated by using a low roughness coefficient of main channel in hydraulic modelling (e.g. Petersen and Fohrer 2010; Yan et al., 2013). In addition of the homogenous characteristic of the river reach, the Manning`s roughness coefficients were therefore set as uniform value of 0.04 for the main channel and 0.06 for the floodplain. The values agreed with those given in standard tables of Manning’s coefficients in scientific literatures (e.g. Chow, 1959). In order to perform a fair comparison, we kept the roughness coefficients the same for all simulations.

RESULTS AND DISCUSSION

Six flood extents with two return periods using three methods were obtained after the simulations were done. We employed a simple aggregate performance measure, *F,* which was used in many inundation modelling studies (e.g. Aronica et al 2002; Horritt et al 2007) to quantitatively compare the simulated flood extents (REC and PMC) to the ones of in situ data (Table 2):

$$F = \frac{A}{A+B+C} \qquad (2)$$

where A is the number of cells correctly predicted by the model, B is the number of cells predicted as wet that is observed dry (over-prediction), C is the number of cells predicted as dry that is observed wet (under-prediction). *F* ranges from 0 to 1, the higher the better.

Table 2 Performance measure *F* of REC and PMC benchmarked to in situ model

	Performance Measure *F*	
	1-in-20 year	1-in-100 year
REC	0.558	0.529
PMC	0.395	0.440

The estimated design floods of three methods differ markedly with each other (Table 1). One of the uncertainties might come from the hydrological frequency analysis of in situ data. The annual maximum flow of 25 years might not be enough for a precise extrapolation of a design flood with large return period (e.g. 1-in-100 year).

The underestimation of REC design floods might be the consequences of the inherent space-time heterogeneity of ungauged basins that induce uncertainties. Even though the hydrological information come from the two large databases (UNESCO 1984; IAHS 2003) which are believed to be reliable (Padi et al., 2011), the gauge networks used by REC are bit poor in terms of the number and distribution of the stations. In particular, very few stations are located in Blue Nile basin, indicating that the constructed empirical envelope curve might miss the hydrological characteristic of the Blue Nile catchment which is dominated by monsoon climate in the Ethiopian Highlands. The specific discharges of Blue Nile basin (with drainage area of 175000 km^2) derived from in situ data is actually above the average of those specific discharges with similar catchment size in Africa continent. In particular, the specific discharge of 1-in-100 year return period is 0.060 m^3/s/km^2 estimated from in situ data, while it is 0.039 m^3/s/km^2 when it is extrapolated from the empirical envelope curve, which leads to an underestimation of the design floods. Given the design floods from REC are underestimated compared to the in situ ones (Table 1, Figure 3), the performance measure *F* of the 1-in-20 year flood extent map seems to be bit low (0.558, Table 2). The quantitative comparison of flood extents shows a slightly better performance of REC than MPC.

The overestimation of PMC design floods are likely due to the large uncertainty accumulated and propagated through the process-based meteorological-hydrological model chain. As stated by Pappenberger et al., (2012), the design floods derived by MPC have limitations due to the fact that it is affected by uncertainties in each components of physical model chain. The meteorological forcing data (i.e. the ERAInterim reanalysis) is too short to calculate high return periods and might be substantially improved by using an enhanced correction routine or better correction data. The quality of the input data set could also be improved by the use of downscaling technique. The land surface scheme (i.e. HTESSEL) results are hampered by the uncertainties in the aspects of model structure, parameters, grid resolution, numerical scheme and topographic data. The model structure is never perfect in hydrological modelling and the large number of parameters leads to considerable uncertainties as well as equifinalities. The surface water fluxes were computed in a coarse grid size of 25 km, which added more uncertainties to the location of upstream boundary in a 90 m-resolution hydraulic model of LISFLOOD-FP. All those uncertainties contribute to largely overestimated design floods (Table 1) and flood extents (Figure 3) compared to the ones derived from in situ data. The *F* value of 0.44 (1-in-100 year) indicates the relatively poor performance of MPC in design flood extents estimation.

CONCLUSIONS

The aim of this study is to investigate the appropriateness of flood extent mapping in Blue Nile using two possible methods: regional envelop curve (REC) and physical model cascade (MPC). The error of design flood estimation in response of flood extent was evaluated quantitatively through the comparison of the benchmark: flood extent simulated using design floods derived from in situ data. The design floods of REC was extrapolated from the empirical envelope curve in Africa prepared by Padi et al., (2011), while the design floods of PMC was calculated from the physical model chain of ECMWF (Pappenberger et al., 2012). The estimated design floods were feed into a 2D hydraulic model, LISFLOOD-FP, to estimate the flood extents. Other boundary conditions and model parameters such as roughness coefficients, topography, and numerical parameters were kept the same for the REC, PMC and In situ model.

The results of this study show that PMC model largely overestimates the design flood extents compared to the benchmark model, with the *F* value of 0.440 for 1-in-100 year return period; while REC underestimates the design flood extents with a slightly higher *F* of 0.529 for the same return period. The results indicate that flood extents derived by PMC and REC might not be appropriate for large scale flood management (e.g. land use planning) and global flood mapping. This is due to the considerable over- and underestimation of flood extents compared to the ones derived from the in situ data. This study is one of the attempts to predict flood extents when hydrological and high resolution topographic data are missing. The poor performances of REC and PMC indicate the challenge to predict flood extents in ungauged basins.

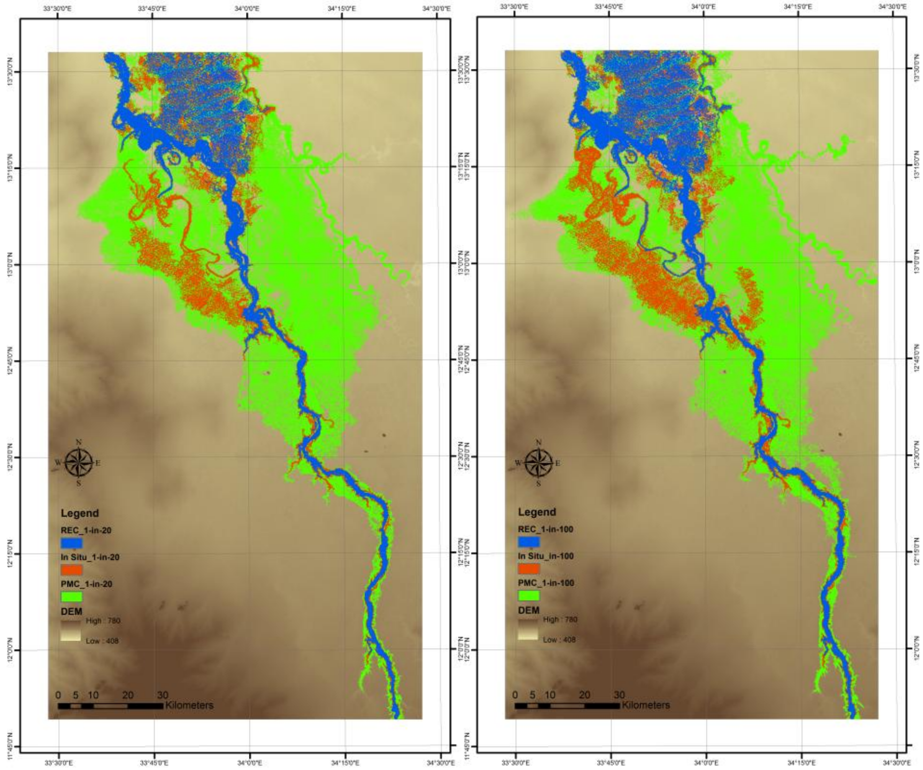

Figure 3 Comparison of flood extents of 1-in-20 year (left panel) and 1-in-100 year (right panel) return period: REC, PMC and In situ

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