Including local rainfall dynamics and uncertain boundary conditions into a 2-D regional-local flood modelling cascade

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1. Introduction

Flood inundation models require appropriate boundary conditions to be specified at the limits of the domain, which commonly consist of upstream flow rate and downstream water level. These data are usually acquired from gauging stations on the river network where measured water levels are converted to discharge via a rating curve. Derived streamflow estimates are therefore subject to uncertainties in this rating curve, including extrapolating beyond the maximum observed ratings magnitude.

On the other hand, the limited number of gauges in reach-scale studies often requires flow to be routed from the nearest upstream gauge to the boundary of the model domain. This introduces additional uncertainty, derived not only from the flow routing method used, but also from the additional lateral rainfall-runoff contributions downstream of the gauging point. These contributions may become important in a sparse gauge network or in events with significant local rainfall.

In this study, a method to incorporate rating curve uncertainty and the local rainfall-runoff dynamics into the predictions of a reach-scale flood inundation model is proposed.

2. Methodology

Discharge uncertainty bounds are generated by applying a non-parametric local weighted regression (LOWESS) approach to stage-discharge measurements for the gauging stations (Coxon et al., 2015). Downstream from these locations, measured rainfall is cascaded into a hydrological model to quantify additional inflows along the main channel. A regional simplified-physics hydraulic model is then applied to combine these inputs and generate an ensemble of discharge and water elevation time series at the boundaries of a local-scale high complexity hydraulic model. This model calculates the depth and velocity fields at the reach scale.

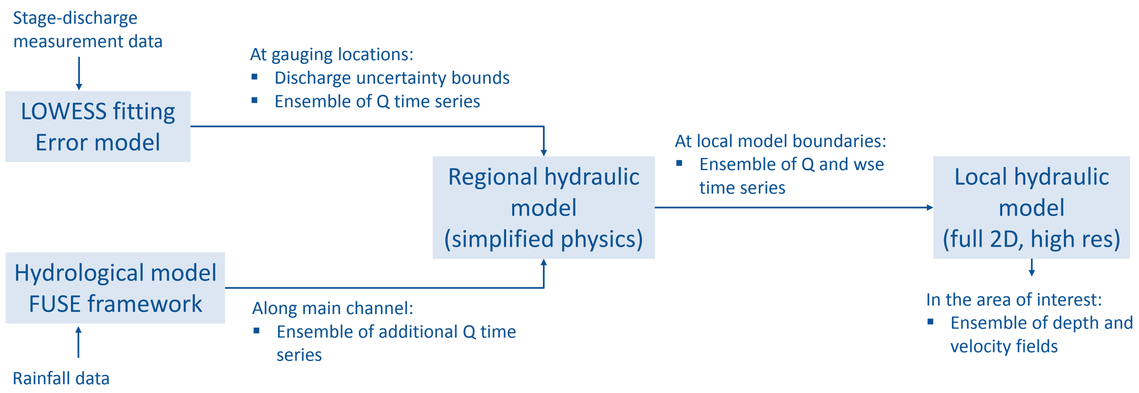

Figure 1. Diagram of the methodology.

3. Case study

The area of interest is a 7 km reach in which the river Severn passes through the city of Worcester in the UK, a low water slope, subcritical reach in which backwater effects are significant. For this domain, the catchment area between flow gauging stations extends over 540 km^2 and the regional model encompasses a total of 60 km of the river (Fig. 2).

The flood event selected as a case study took place on the 20th July 2007 and is part of a series of destructive floods that occurred in the United Kingdom during that summer season.

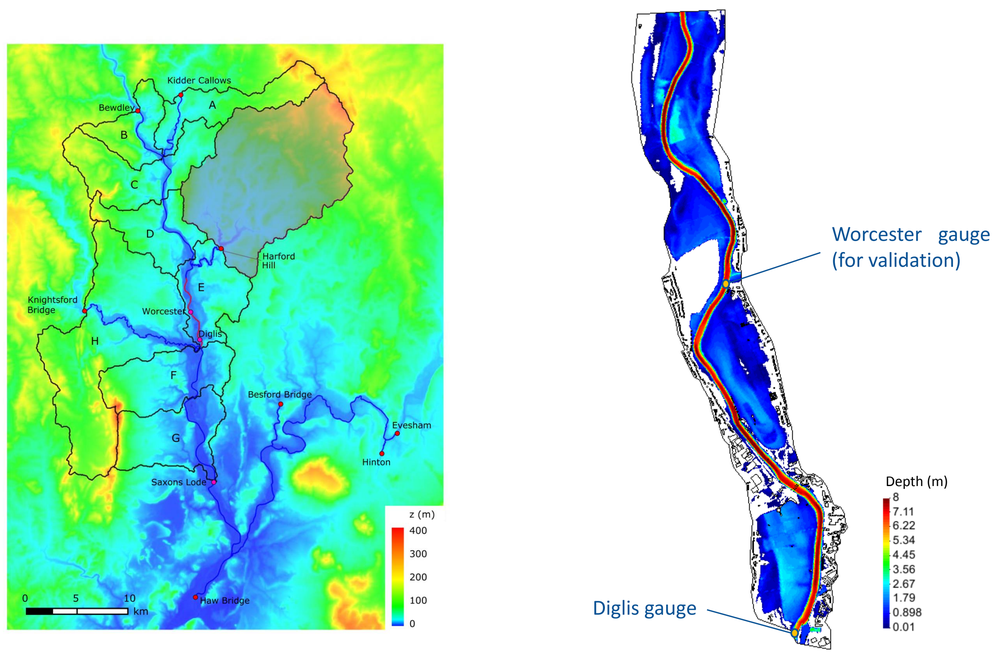

Figure 2. Regional model domain, the Harford Hill catchment (shaded in grey), sub-catchment delineation and location of gauging stations (red dots) used to provide flow boundary conditions (left). Inundation depth predicted by the local model and location of control points (right).

4. Results: quantification of uncertainty in rating curves

The discharge uncertainty was estimated at two gauging stations: Bewdley and Knightsford Bridge (Fig. 2), based on the magnitude of discharge and closeness to Worcester area.

A non-parametric local weighted regression approach was used for fitting a rating curve from the stage-discharge measurements at each station (Coxon et al., 2015). The uncertainty of the fit was quantified to define discharge uncertainty bounds (Fig. 3).

A 1st-order autoregressive model was then used to generate serially-correlated errors. A total of 200 time series of errors were generated and then added to the original discharge time series.

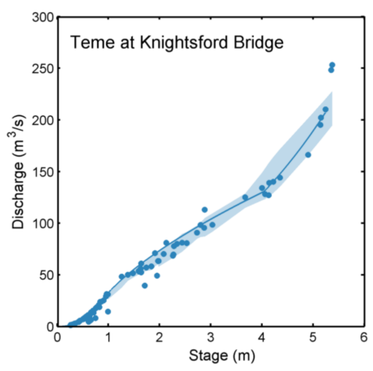

Figure 3. Stage-discharge measurements, LOWESS fit and uncertainty bounds for Knightsford Bridge gauging station.

5. Results: evaluation of local rainfall-runoff dynamics

In order to evaluate the local rainfall-runoff dynamics, a semi-distributed hydrological model comprising 8 sub-catchments was developed (Fig. 2). Lumped hourly measured rainfall and PET data for the year 2007 were obtained for each sub-catchment.

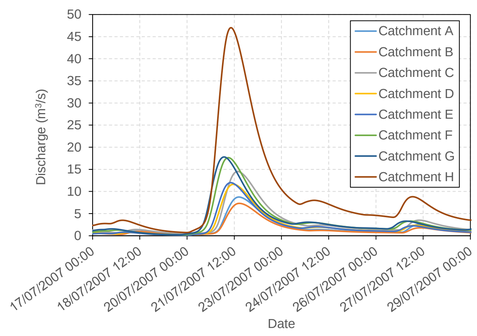

Figure 4. Average surface runoff contributions of each sub-catchment to the streamflow at Saxons Lode. The hydrographs depict the mean discharge obtained with the selected 200 rainfall-runoff models.

Four hydrological models from the FUSE framework (Clark et al., 2008) were set up to simulate the rainfall-runoff process over each sub-catchment. A total of 10,000 simulations were run for each model structure, considering different parameters sets.

Given the lack of gauging stations in the model domain, the structure and parameter selection was based on the best performing models from the Harford Hill catchment (shaded in grey in Fig. 2). A total of 200 outflow hydrographs were obtained for each sub-catchment, which were subsequently introduced in the hydraulic model along the main channel.

6. Results: performance of flood model cascade

At the regional scale, a 2-dimensional hydraulic model that solves the local inertial approximation of the shallow water equations was applied to route the flow (Bates et al., 2010; Neal et al., 2015), whereas the full form of these equations was solved at the local scale to predict the urban flow field (Bladé et al., 2014). This nested approach hence allows an examination of water fluxes from the catchment to the building scale, while requiring short setup and computational times.

The effect of including rainfall dynamics and uncertain boundary conditions on model performance was quantified using observed flood extent data and measured water levels.

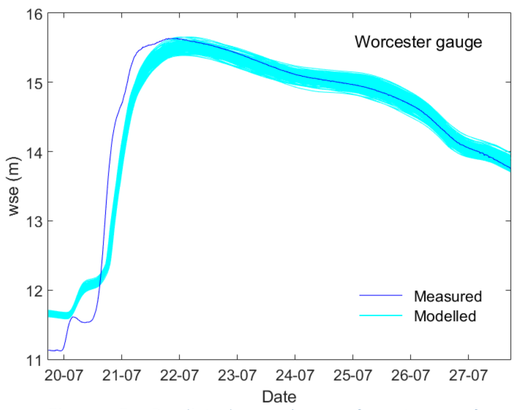

Figure 5. Predicted envelope of water surface elevation at Worcester gauge and measured values.

	WSE time series at Worcester (19 Jul – 27 Jul)		Spatial inundation prediction (25 Jul – 06:34 h)	
	NSE	RMSE (m)	Flood extent (km^2)	Flood area index (%)
Minimum	0.92	0.28	1.69	78.8
Maximum	0.95	0.36	1.80	81.9

Table 1. Evaluation of the local model performance.

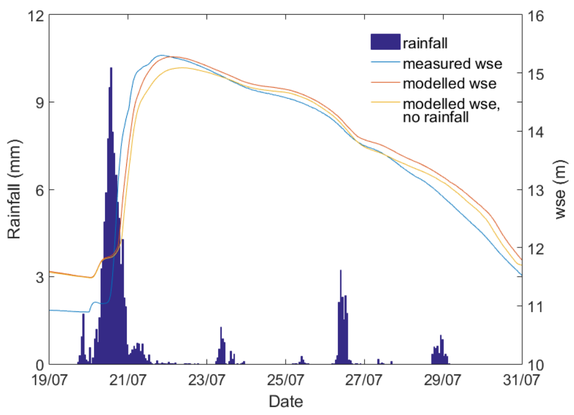

Figure 6. Comparison of predicted average water surface elevations at Diglis gauge with and without local rainfall-runoff contribution and measured values.

The incorporation of the local rainfall-runoff contribution improves the prediction of the magnitude and timing of the flood peak in the regional model (Fig. 6 shows the predictions at the downstream boundary of the local model), which in turn improves the predictions of the local model.

The measured water levels in Worcester gauge fall within the prediction interval, with high NSE values (Fig. 5 and Table 1). The flood extent prediction is likewise in agreement with observed data.

The external forcing uncertainty leads to small variations in model performance measures (Table 1).

7. Conclusions

We have developed a method for incorporating the local rainfall dynamics and uncertain boundary conditions into the predictions of a reach-scale flood model. Their inclusion led to a more accurate prediction of the magnitude and timing of the flood peak, in spite of the unusual structure of the rain episode and the complexity of the River Severn system. The findings highlight the importance of estimating these contributions for accurate prediction of river flows and inundation.

References

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