A coupled hydrological and hydrodynamic model for flood simulation

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A Coupled Hydrological and Hydrodynamic Model for Flood Simulation

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Abstract

This paper presents a new flood modelling tool developed by coupling a full 2D hydrodynamic model with hydrological models. The coupled model overcomes the main limitations of the individual modelling approaches, i.e. high computational costs associated with the hydrodynamic models and less detailed representation of the underlying physical processes related to the hydrological models. When conducting a simulation using the coupled model, the computational domain (e.g. a catchment) is first divided into hydraulic and hydrological zones. In the hydrological zones that have high ground elevations and relatively homogeneous land cover or topographic features, a conceptual lumped model is applied to obtain runoff/net rainfall, which is then routed by a group of pre-acquired 'unit hydrographs' to the zone borders. These translated hydrographs will be then used to drive the full 2D hydrodynamic model to predict flood dynamics at high resolution in the hydraulic zones that are featured with complex topographic settings, including roads, buildings, etc. The new coupled flood model is applied to reproduce a major flood event occurred in Morpeth, Northeast England in September 2008. Whilst producing similar results, the new coupled model is shown to be computationally much more efficient than the full hydrodynamic model.

Key words: Flood modelling, hydrodynamic model, coupled hydrological and hydrodynamic model, Godunov-type finite volume method, water balance model, unit hydrograph method

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1. Introduction

A growing number of severe floods have been witnessed over the past two decades in the UK. In the autumn of 2000, tropical cyclones caused heavy rainfall and consequently severe flooding across the UK. The successive series of floods caused two deaths and the inundation of 7,406 properties with a total economic loss of £500 million (Met Office, 2014). In January 2005, Carlisle experienced the worst flood since 1822, leading to 1,844 properties flooded, 3 deaths and over £400 million of economic losses. Two years later in 2007, England and Wales were hit by severe flooding, which caused 14 deaths and left thousands of people suffering from prolonged misery. More than 55,000 homes and 6,000 businesses were flooded, resulting in the highest number of search-and-rescue missions in the UK since the Second World War (Marsh and Hannaford, 2007). Nationwide flood events also occurred during the course of 2012 and through the winter into 2013, which caused at least nine deaths and an economic loss of about £1 billion. With the ongoing climate changes and more intensive human activities, Evans et al. (2004) predicted that river and coastal flood risks could increase up to 20-fold and the resulting economic losses could increase to between £1.5 billion and £21 billion by the 2080s. Completely eliminating flood risks is technically and economically impossible, and so integrated strategies to manage flood risk must be in place to avoid or mitigate the adverse impacts of floods on individuals and communities (Pitt, 2008). Flood modelling has provided an indispensable tool to inform the development of flood risk management strategies.

Substantial research effort has been made to improve the numerical accuracy and computational efficiency of 2D hydrodynamic flood models. But the existing hydrodynamic models in many cases are still computationally prohibitive for large-scale applications, especially in urban environments where high-resolution representation of complicated topographic features is necessary (e.g. Hunter et al., 2007). Hydrological models have been widely used in predicting flooding and hydrological processes in rural catchments, which require less computational time at the price of representing less detailed physical processes. Coupling hydrodynamic models with hydrological models may overcome the shortcomings of either type of the modelling approaches. Although hydrodynamic and hydrological models have been separately used in many practical applications, coupling of these two types of models for urban flood simulation has rarely been reported in the literature. Therefore, the aim of this work is to develop a robust and efficient tool for practitioners to perform urban flood modelling by coupling a hydrodynamic/hydraulic model with hydrological models.

There are normally three main types of methods for coupling hydraulic and hydrological models: external coupling, internal coupling and full coupling (Morita and Yen, 2002). The simplest and most common type is external coupling which usually employs the pre-acquired hydrographs from hydrological models as the upstream and/or lateral boundary conditions for the hydraulic models, to provide a one-way but seamless transition (e.g. Anselmo et al., 1996; Correia et al., 1998; Lastra et al., 2008; Gül et al., 2010; Bravo et al., 2012). This coupling method has also been widely applied in flood routing through complicated river network systems (e.g. Whiteaker et al., 2006; Lian et al., 2007; Bonnifait et al., 2009; Mejia and Reed, 2011; Paiva et al., 2011; Kim et al., 2012; Lerat et al., 2012).

The internal coupling method has also been reported in the literature (Thompson, 2004), in which the governing equations of the hydraulic models and hydrological models are solved separately, with information at the shared boundaries updated and exchanged at each or several computational time step (Morita and Yen, 2002). For example, Thompson (2004) linked MIKE-SHE hydrological and MIKE 11 hydraulic models at several prescribed points along the river. Water levels calculated from MIKE 11 can be transferred to MIKE-SHE, and overland flows calculated by MIKE-SHE are fed back to MIKE 11 at these points throughout a simulation. Few studies report full coupling, due to the complication of reformulating and simultaneously solving governing equations in a single code base.

To relax the restriction of the computationally demanding hydrodynamic models for high-resolution urban flooding modelling, this study presents a new method for coupling hydraulic / hydrodynamic models with hydrological models for application in urban catchments. The proposed numerical method falls into the external coupling category. During a simulation, hydraulic and hydrological zones are firstly specified according to a design flood event. The runoff or net rainfall calculated by a lumped conceptual model, known as a Water Balance Model (WBM) (Walker and Zhang, 2002), in the hydrological zones is routed with a group of pre-acquired 'unit hydrographs' to the hydraulic cells at the shared boundaries for higher-resolution simulations utilising a full 2D hydrodynamic model (Liang, 2010) in hydraulic zones. It should be noted that, although drainage system network modelling is usually an important component in urban flood modelling, it is not included in the current modelling strategy as the flood event under consideration was mainly caused by the fluvial process and overtopping and damage of flood defences.

2. Coupled hydrological and hydrodynamic model

This section introduces the coupled hydrological and hydrodynamic model as proposed, in which a catchment is required to be firstly divided into hydraulic zones and hydrological zones according to a design flood event.

2.1 Hydraulic and hydrological zones

Before an actual simulation, the full 2D shallow flow model (Liang, 2010) is used to predict a design flood event in the research domain, driven by design rainfall and design inflow hydrographs at the river boundary points. To reduce computational time, the deign flood simulation is run on lower-resolution grids to rapidly obtain the preliminary inundation extent. The areas inundated by the design flood are preliminarily regarded as hydraulic zones, while the rest of the domain is specified as hydrological zones. The design flood event will be chosen to be more severe than the simulated event to ensure the validity of the domain partition. In the adopted one-way external coupling approach, flow from hydraulic zones to hydrological zones is not expected. Areas less likely to be inundated, with relatively higher elevations and steeper local slopes, may be also specified as hydrological zones, which can be determined by checking the DEM and land cover maps of the research domain.

2.2 Full 2D hydrodynamic model

Assuming hydrostatic pressure distribution and omitting the viscous terms, the well-balanced shallow water equations in the differential hyperbolic conservation form can be written as:

$$\frac{\partial \mathbf{u}}{\partial t} + \frac{\partial \mathbf{f}}{\partial x} + \frac{\partial \mathbf{g}}{\partial y} = \mathbf{s} \,. \qquad (1)$$

where t denotes time; x and y are the Cartesian coordinates, and the vectors representing conservative variables ($\mathbf{u}$), fluxes ($\mathbf{f}$ and $\mathbf{g}$) and source terms ($\mathbf{s}$) are given by (Liang and Borthwick, 2009):

$$\mathbf{u} = \begin{bmatrix} \eta \\ uh \\ vh \end{bmatrix}, \qquad \mathbf{f} = \begin{bmatrix} uh \\ u^2 h + \frac{1}{2} g(\eta^2 - 2\eta z_b) \\ uvh \end{bmatrix},$$

$$\mathbf{g} = \begin{bmatrix} vh \\ uvh \\ v^2 h + \frac{1}{2} g(\eta^2 - 2\eta z_b) \end{bmatrix}, \qquad \mathbf{s} = \begin{bmatrix} ss \\ -\frac{\tau_{bx}}{\rho} - g\eta \frac{\partial z_b}{\partial x} \\ -\frac{\tau_{by}}{\rho} - g\eta \frac{\partial z_b}{\partial y} \end{bmatrix}, \qquad (2)$$

in which η represents water level; uh and vh give the unit-width discharges, with h, u and v being the water depth and x- and y-direction velocity components, respectively; ss represents external source terms (e.g. rainfall / runoff); ρ is the density of water; z_b is the bed elevation; and g is the gravitational acceleration. The bed friction stress terms, τ_{bx} and τ_{by}, may be estimated using:

$$\tau_{bx} = \rho C_f u\sqrt{u^2+v^2} \text{ , and } \tau_{by} = \rho C_f v\sqrt{u^2+v^2} \text{ ,} \tag{3}$$

where $C_f = gn^2 / h^{1/3}$ is the bed roughness coefficient with n being the Manning coefficient.

The above shallow water equations are solved using a finite volume shock-capturing Godunov-type scheme, incorporated with an HLLC approximate Riemann solver for estimating the interface fluxes. Detailed implementation and validation of the numerical scheme can be found in Liang (2010).

2.3 Hydrological model

In this study, the lump conceptual Water Balance Model (WBM) (Walker and Zhang, 2002) is employed to estimate runoff production because of its simplicity and high efficiency. This conceptual WBM model is illustrated in Figure 1, in which the catchment is treated as a container with a rainfall input and several outputs including infiltration, evapotranspiration and runoff. The capacity of the container is the maximum surface storage of the catchment, which mainly depends on surface ponding, plant interception, etc. Once the water volume inside the container exceeds its capacity, surface runoff will occur. Interflow and base flow are not relevant to the current study and therefore neglected for simplification. The net rainfall transferring onto surface runoff can be evaluated by:

$$RR = PP - EE - f - SS \text{ ,} \tag{4}$$

where RR is the net rainfall or surface runoff, PP is the total rainfall, EE is the evapotranspiration, f is the infiltration, and SS is the maximum surface storage.

In Equation (4), evapotranspiration may be considered negligible in the current study as only inundation events caused by relatively short-duration intense rainfall are considered. Additionally, the maximum surface storage can be ignored because each of the WBM domains is either a hydrological zone or an individual cell in hydraulic zones subdivided at relatively high resolution, which is usually covered by homogeneous topographic features with negligible ponding effect. Infiltration is assumed to be zero in the impermeable areas including rooftops, and estimated using the Green-Ampt equation (Green and Ampt, 1911) in the permeable areas:

$$f = \frac{dFF}{dt} = -K_s\left(\psi_f \frac{\theta_s - \theta_a}{FF} + 1\right), \tag{5}$$

where FF is the cumulative depth of infiltration; K_s is the saturated hydraulic conductivity; ψ_f is the matric pressure at the wetting front; θ_a is the initial moisture content; θ_s is the saturated moisture content. The selection of parameter values for different soil textures follows Rawls et al. (1982) and Rawls and Brakensiek (1985). This equation is also used to estimate the infiltration (part of the *ss* term in Eq. (2)) in the full 2D shallow flow model in the hydraulic zones.

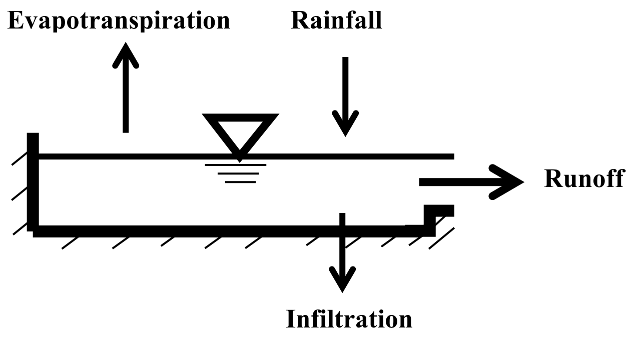


Figure 1 The conceptual representation of the adopted Water Balance Model.

2.4 Coupling method

The external coupling method is adopted in this work, which generally employs pre-acquired hydrographs from a hydrological model as the upstream and/or lateral boundary conditions to drive the hydraulic model, providing a one-way but seamless transition. Herein, the net rainfall that leads to surface runoff in hydrological zones (the left part in Figure 2) is firstly calculated using the WBM hydrological model. A 'unit hydrograph' ('UH') method is then used to derive the corresponding hydrographs at the hydraulic cells at the border between the hydraulic and hydrological zones to drive the high-resolution hydrodynamic simulations in hydraulic zones (the right part in Figure 2). Whilst providing a reliable approach to derive the boundary hydrographs to drive the full 2D hydrodynamic model, the unit hydrograph method is easy to implement in this context. This work introduces a novel means to apply this classic method in flood modelling. As mentioned previously, flow from the hydraulic zones to hydrological zones is not considered.

It should be noted that WBM model is not only applicable to the hydrological zones for calculating the net rainfall and lumped runoff production but also to the hydraulic zones to account for the hydrological processes in each of the hydraulic cells (e.g. the infiltration as mentioned before). In the hydraulic cells, the net rainfall resulting from the WBM model will be directly fed into the full 2D shallow flow model as an external source term.

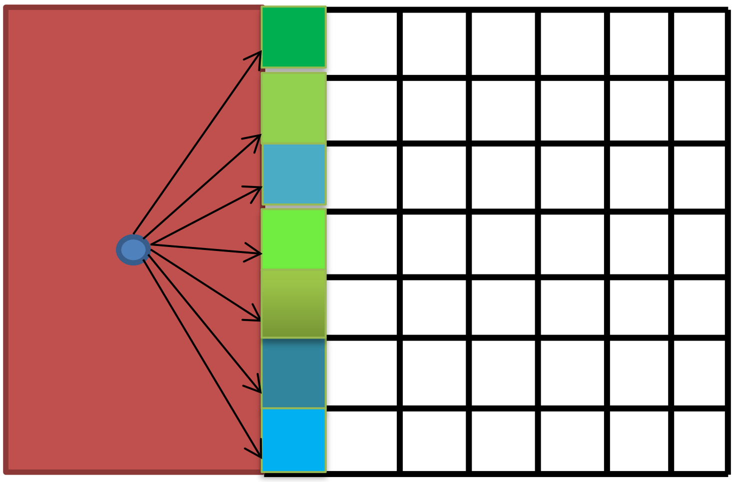


Figure 2 The schematization of the divided catchment.

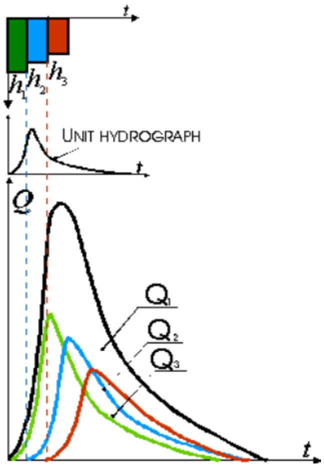


Figure 3 The unit hydrograph method (VICAIRE, 2006).

The unit hydrograph represents the hypothetical response of a catchment at the outlet to a unit input of uniform net rainfall. In this work, the concept of a unit hydrograph has been extended so that it is no longer limited to providing hydrograph at the catchment outlet, but applicable to the catchment zone border. In order to generate a 'unit hydrograph' at the zone border, the hypothetical net rainfall (10mm for 15 minutes) is applied to the hydrological zones, and the integrated full 2D shallow flow and WBM model is used to simulate the rainfall induced surface flow and subsequently derive the hydrographs at each of the bordering cells. These hypothetical hydrographs can be regarded as a group of generalised unit hydrographs. During real simulations, these 'unit hydrographs' will be scaled and superimposed according to real net rainfall pattern in the hydrological zones (as shown in Figure 3) to provide accumulative hydrographs along the zone border. These accumulative hydrographs will then provide external source terms in the full 2D shallow flow model in those bordering hydraulic cells to create flooding in the hydraulic zones.

2.5 Summary of the simulation procedure

In summary, to apply the new coupled model to support flood modelling, the following steps will be taken:

1) Collect and process spatial and non-spatial data for setting up models;
2) Run the full 2D shallow flow model on a coarse grid to produce the preliminary inundation extent for a design flood event;
3) Specify hydrological zone and hydraulic zones according to the inundation extent obtained in Step 2) as well as DEM and land cover maps;
4) Use the full 2D shallow flow model to generate a group of 'unit hydrographs' at the zone border cells, and subsequently obtain the scaled hydrographs according to 'real' net rainfall;
5) Run the coupled model to simulate observed/design events, driven by the scaled hydrographs and rainfall input (if necessary);
6) Process and interpret simulation results.

3. Case study site and data

In this study, the newly developed coupled flood modelling tool is applied to reproduce a major flood event occurred in Morpeth, UK in 2008. This section provides the necessary description of the case study site, the event and the data required for the simulations.

3.1 Morpeth and the flooding issue

Morpeth is an ancient market town located in the Wansbeck Catchment of the North East England, UK. The Wansbeck Catchment covers a total of 331 km^2, and the catchment area upstream of Morpeth is approximately 287.3 km^2 (CEH, 2018). In Morpeth, the Wansbeck River is joined by three smaller tributaries, i.e. Cotting Burn, Church Burn and Postern Burn. The main reach of the Wansbeck River has an active floodplain ranging from 100 m to 300 m in width, in which Morpeth is located (Environment Agency, 2005). Due to its location, Morpeth is particularly vulnerable to flooding, with 1,407 properties in the town centre identified to be at high risk of flooding (Environment Agency, 2009b).

In history, Morpeth has experienced many flood events of varying levels of severity, with the most recent floods occurred in 2008 and 2012. Between 4th and 6th September 2008, North East England was hit by an extremely heavy storm and the Morpeth weather station recorded 152.3 mm of rainfall, equivalent to 235% of the average rainfall for September (Met Office, 2008a). The catchment was already saturated due to the antecedent rainfall in July and August, which caused more surface runoff and rapid rise of river levels and discharges (JBA Consulting, 2008). The peak discharge reached 357 m^3/s at the Mitford flow station located about 2.2 km upstream of Morpeth. The high upstream discharge combined with local overland inflow led to the overtopping and damage of flood defences for the first time since they were built about 50 years ago. The resulting floods inundated more than 950 properties in the town centre. All road networks within the town centre were largely affected. Hundreds of residents were forced to evacuate, and many of them were not able to live in their home for months. Causing over £10 million of direct damage (Coolgeology, 2018), the event was estimated to have a 1 in 137 year return period and was recorded as the worst flood in Morpeth (Environment Agency 2009a).

Table 1 Data used in this study.

Data	Sources	Purpose
Rainfall	Environment Agency	Model input
River discharge	Environment Agency	Model input
DTM	Environment Agency	Provide basic topography
Buildings	OS MasterMap	Refine DTM to take into account the effect of buildings
Flood defences	Field work	Refine and correct DTM
Land cover map	OS MasterMap	Classify permeable and impermeable surfaces and define simulation domain
Soil type map	1. British Geological Society 2. National Soil Resources Institute	Select general infiltration parameters
Observed water depth at critical points	2008 Morpeth Flood Summary Report	Model validation
Surveyed flood extents	2008 Morpeth Flood Summary Report	Model validation

3.2 Data

The data used in this work for setting up and validating models are summarised in Table 1, including non-spatial data (observed records of rainfall, river discharge, water depth), and spatial data (DTM, land cover map, soil types and flood extents). Figure 4 shows the extracted simulation domain and the location of all rain gauges in the catchment. High-quality continuous rainfall records for the current event are mainly available from four rain gauges (i.e. Wallington, Harwood Burn, Font Reservoir and Newbiggin). An inverse distance weighting method, i.e. Shepard's method (Shepard, 1968), is utilised to obtain the rainfall distribution to support flood simulations at the town centre. The resulting hourly rainfall is shown in Figure 5, in which the highest daily rainfall of 72.75 mm is observed to occur on 6th September, correlating well with the recorded peak flow discharge of 357 m^3/s (also occurred on 6th September). The discharge hydrograph recorded at the Mitford gauge station at a 15-minute interval is also illustrated in Figure 5. The Mitford station (denoted as 'A' in Figure 4) is located at the confluence point of Upper Wansbeck River and Font River with an upstream catchment area of approximately 282 km^2. The recorded discharge hydrograph provides perfect upstream inflow boundary conditions for the research domain.

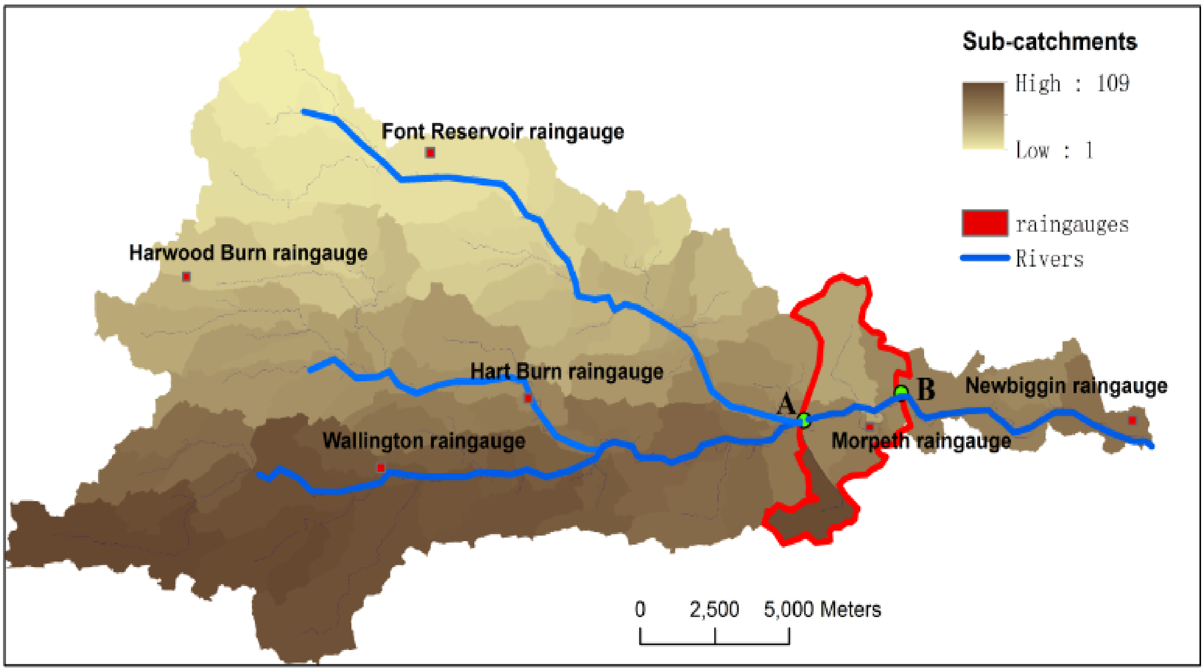


Figure 4 The extracted simulation domain and location of rain gauges in the Wansbeck Catchment.

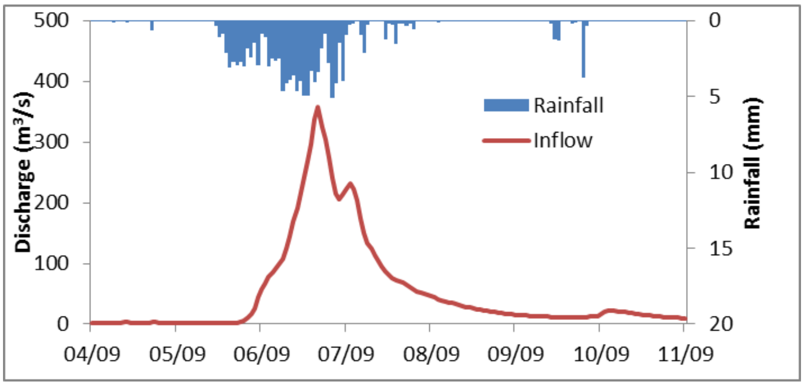


Figure 5 The rainfall and discharge series on 4-11th September 2008.

A 2 m × 2 m high-resolution LiDAR DTM is available for the case study site. The DTM has been validated to have a vertical *RMSE* of about 20 cm (Parkin, 2010). Surveyed river cross-section data are used to correct the DTM to give better representation of river geometry. Extra fieldwork has been carried out to measure the location and height of the flood defences to further correct the DTM. With the building outlines and locations available from OS MasterMap, the buildings are represented on the DTM by raising the ground level by 10 m. Land cover data are also obtained from OS MasterMap to define permeable and impermeable zones in the computational domain. Based on the USDA soil texture, the general Green-Ampt infiltration parameters can be decided (Rawls et al., 1982; Rawls and Brakensiek, 1985), as shown in Table 2. Due to the almost saturated soil prior to the flood event, the initial moisture contents are all set to be 'saturated'.

Table 2 Green-Ampt soil parameters.

USDA soil texture	Saturated moisture content θ_s (cm^3/cm^3)	Saturated hydraulic conductivity K_s (cm/h)	Matric pressure at the wetting front Ψ_f (cm)
Clay loam	0.464	0.10	20.88
Sandy clay loam	0.398	0.15	21.85

Finally for model validation, flood depth and extent data are made available from a post-event investigation carried out by Parkin (2010). The Morpeth Flood Action Group has reviewed the inundation extent maps and provided further clarifications (further details can be found in Parkin (2010)).

4. Results and Discussion

In this section, the coupled model is applied to reproduce the 2008 Morpeth flood event, and the simulation results are compared with observations and also the high-resolution numerical predictions obtained from the full 2D shallow flow model. As explained previously, the major cause of the 2008 Morpeth event was fluvial flooding from defence damage and overtopping, the effect of drainage systems is not considered in the simulation results presented here.

4.1 Simulation domain and catchment Division

The simulation domain is selected to be a 19.16 km^2 sub-catchment where Morpeth is located. The location of the sub-catchment within the entire Wansbeck Catchment is illustrated in Figure 4 (enclosed by the red line). On the map, the Mitford flow station is located at point 'A', through which all of the upstream flows converge. The sub-catchments downstream of point ‘B’ have no effect on Morpeth, which provides a natural downstream boundary for the selected computational domain.

The extracted sub-catchment is divided into hydraulic and hydrological zones to facilitate the setup of the coupled model. The design rainfall over the catchment and design hydrograph at the Mitford flow station, with the return period of 200 years, are first obtained using the Depth-Duration-Frequency (DDF) curves and the Revitalised Flood Hydrograph (ReFH) model for the Wansbeck Catchment, available in the Flood Estimation Handbook (FEH) (Kjeldsen, 2007). Subsequently, a design flood event is then generated by the full 2D shallow flow model based on the design rainfall hyetograph and design hydrograph. The resulting flood extent can be then employed as a reference to divide the extracted sub-catchment into hydraulic and hydrological zones.

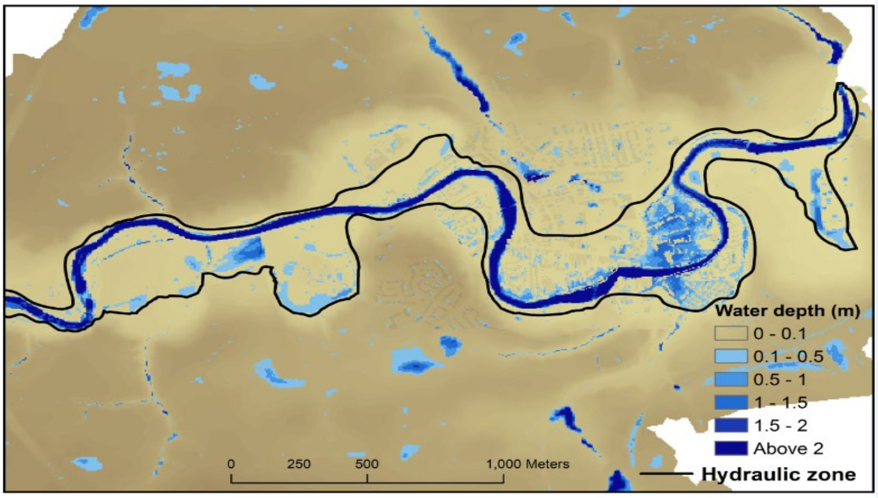


Figure 6 Inundation extent of the 1 in 200 year design flood in the extracted sub-catchment.

When classifying the hydraulic and hydrological zones, only rough inundation extent is required and so simulations can be performed on a coarse grid at 5 m resolution to reduce computational cost. The resulting inundation extent is displayed in Figure 6. The fluvial inundation area can be preliminarily regarded as a hydraulic zone, and local adjustments may be made according to the land cover. For example, in Figure 6, the inundation area around point ‘A’ may be caused by local rainfall, but it is still included in the hydraulic zone because it is mostly covered by buildings and close to the fluvial inundation area. The final hydraulic zone is outlined in Figure 6 and the remaining areas are regarded as the hydrological zone. Since the return period of the September 2008 flood event is evaluated as 137 years, the catchment division scheme from the 1 in 200 year design flood event is considered suitable for the assigned simulations.

4.2 Model setup

The extracted sub-catchment / simulation domain is discretised at 2m resolution to represent the complex urban topography. The numbers of different types of computational cells in the domain are listed in Table 3. In the simulation using the full 2D hydrodynamic model, a total of 4,789,781 cells are used to solve the shallow water equations to predict rainfall-induced flooding process. In the coupled model simulation, only 269,480 cells in the hydraulic zone are handled by the full 2D model but the hydrological zone covered by 4,520,301 cells is treated as a lumped area using hydrological models.

Table 3 The number of different types of cells in the computational domain.

Cell type	Domain cells	Hydraulic cells	Hydrological cells
Cell number	4,789,781	269,480	4,520,301

For all of the simulations, a steady flow in the river channel, driven by a steady low inflow of 10 m^3/s at the inlet, is obtained as the initial conditions for the full 2D shallow flow model. The Manning coefficient $n = 0.02$ $m^{-1/3}$ s and the acceleration due to gravity $g = 9.81$ m/s^2 are used.

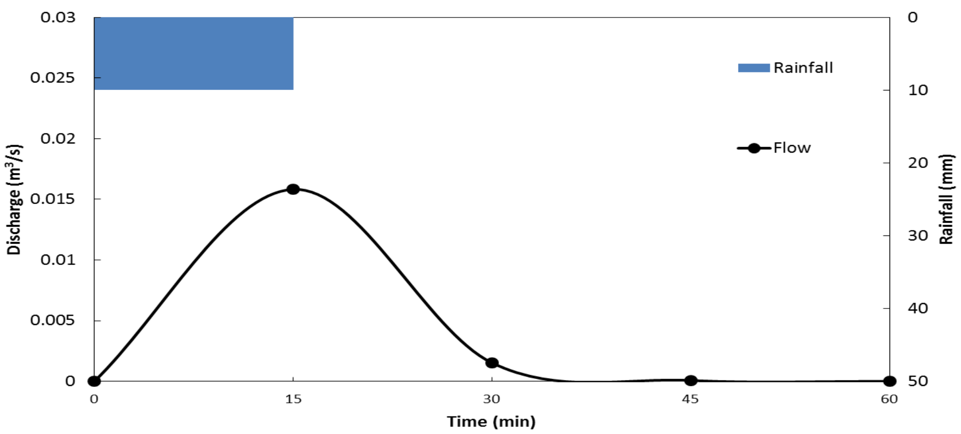


Figure 7 An example of ‘unit hydrograph’ at the zone border cells.

Before reproducing the 2008 Morpeth flood event using the coupled model, the full 2D shallow flow model is employed to create the ‘unit hydrographs’ at the hydraulic and hydrological zone border cells under a uniform net rainfall of 10 mm of 15-minute duration in the model domain. Figure 7 displays a ‘unit hydrograph’ in one of the border cells as produced. The unit hydrograph is then scaled and superimposed according to the real net rainfall pattern to generate an accumulative hydrograph from the hydrological zone at that particular cell, as illustrated in Figure 8. The accumulative hydrographs in the border cells will be then used to drive the simulation in the hydraulic zone.

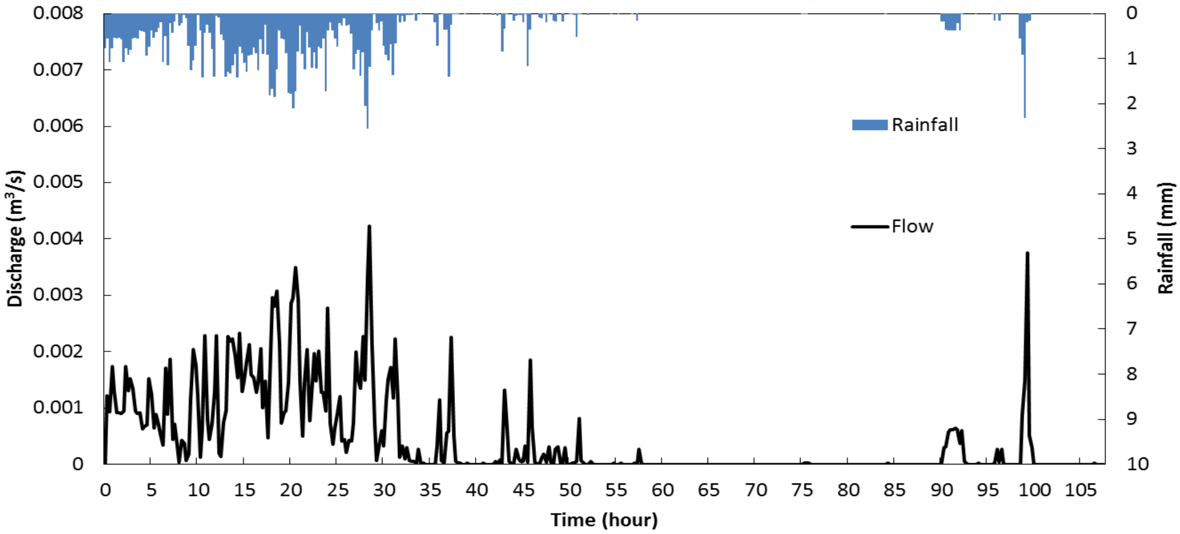


Figure 8 An example of the accumulative hydrograph at a zone border cell.

Table 4 Details of the critical points for recording time histories of water depth.

Critical points	Location	Coordinates		Description
		Easting	Northing	
1	Mitford Road	419223	586162	Between houses, to assess flow between buildings
2	High Stanners	419549	586138	Showing out of bank flow across the green area and flooded houses
3	High Stanners	419571	585979	Undefended area next to the river and hydrological zone
4	Central Morpeth	419818	585764	Undefended area next to the river
5	Low Stanner	420123	586085	In a small lane
6	Middle Greens	420222	585820	Showing extensive surface water flooding and flow through defences

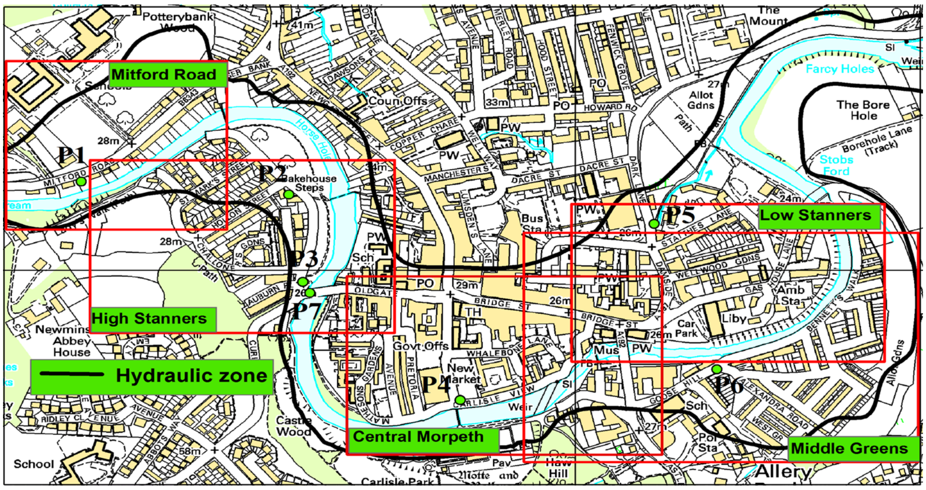


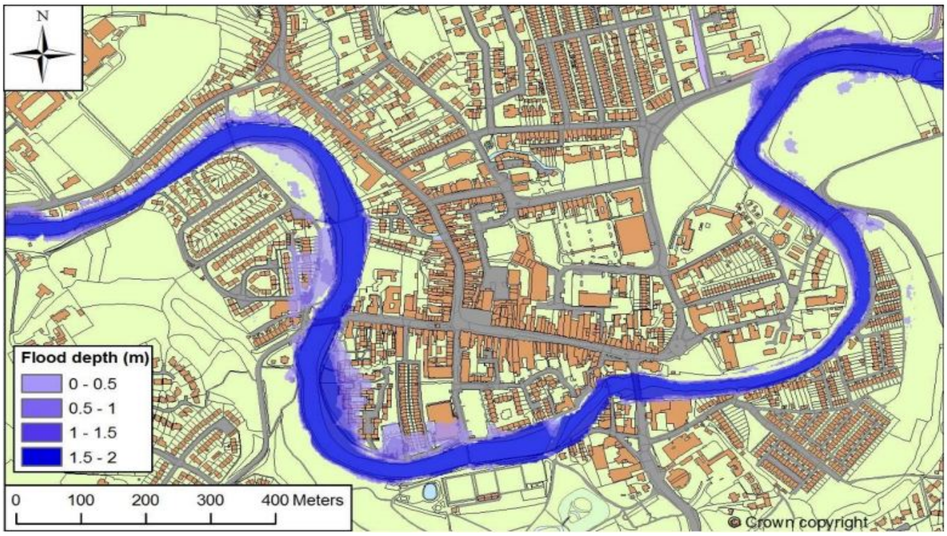
Figure 9 The location of the critical points.

4.3 Results and discussion

The 2008 Morpeth flood is reproduced for 50 hours starting at 4pm on the 5th September on a desktop PC with an Intel$^{(R)}$ Core$^{(TM)}$ i5 CPU. Six critical points located at different parts of the town centre are selected to record the time histories of water depths to compare with measurements. Details of these critical points are documented in Table 4 and Figure 9.

In Figures 10 - 13, the inundation maps at 11am, 1pm, 3pm and 5pm on 6th September obtained from the coupled model are compared with those obtained using the full 2D shallow flow model, as well as the post-event investigation. The full 2D shallow flow model has produced similar inundation extents, in comparison with the coupled model in the hydraulic zone at 11am and 1pm. However, the inundation extent at 3pm from the coupled model is larger at the left bank in Central Morpeth and at the right bank in High Stanners. At 5pm, this difference becomes marginal again. This may be explained by the coupling method used in the coupled model. The adopted 'unit hydrograph' approach may route the flow from the hydrological zone to the hydraulic zone faster than using the full 2D shallow flow model, and therefore the flow from the hydrological zone predicted by the coupled model may join the fluvial flood in the hydraulic zone earlier to produce a larger inundation extent at around 3pm. However, this effect is less pronounced when the rainfall reduces, and so the two inundation extents become similar again at 5pm, after the intense rainfall period terminates.

In comparison with the post-event investigated inundation maps, the two simulated inundation extents, respectively from the coupled model and the full 2D shallow flow model, are observed to be larger at 11am and 1pm. A closer match has been produced for flood extents at 3pm. At 5pm the simulated inundation extents from both models achieve the closest overall match with the post investigation survey. The cause of this discrepancy might be limitations in the measured data. The Environment Agency debris data and the crowd-sourced information may not represent the full flood propagation process, and this means that the maximum inundation extent (at 5pm) is likely to be much more reliable than the records at other times.

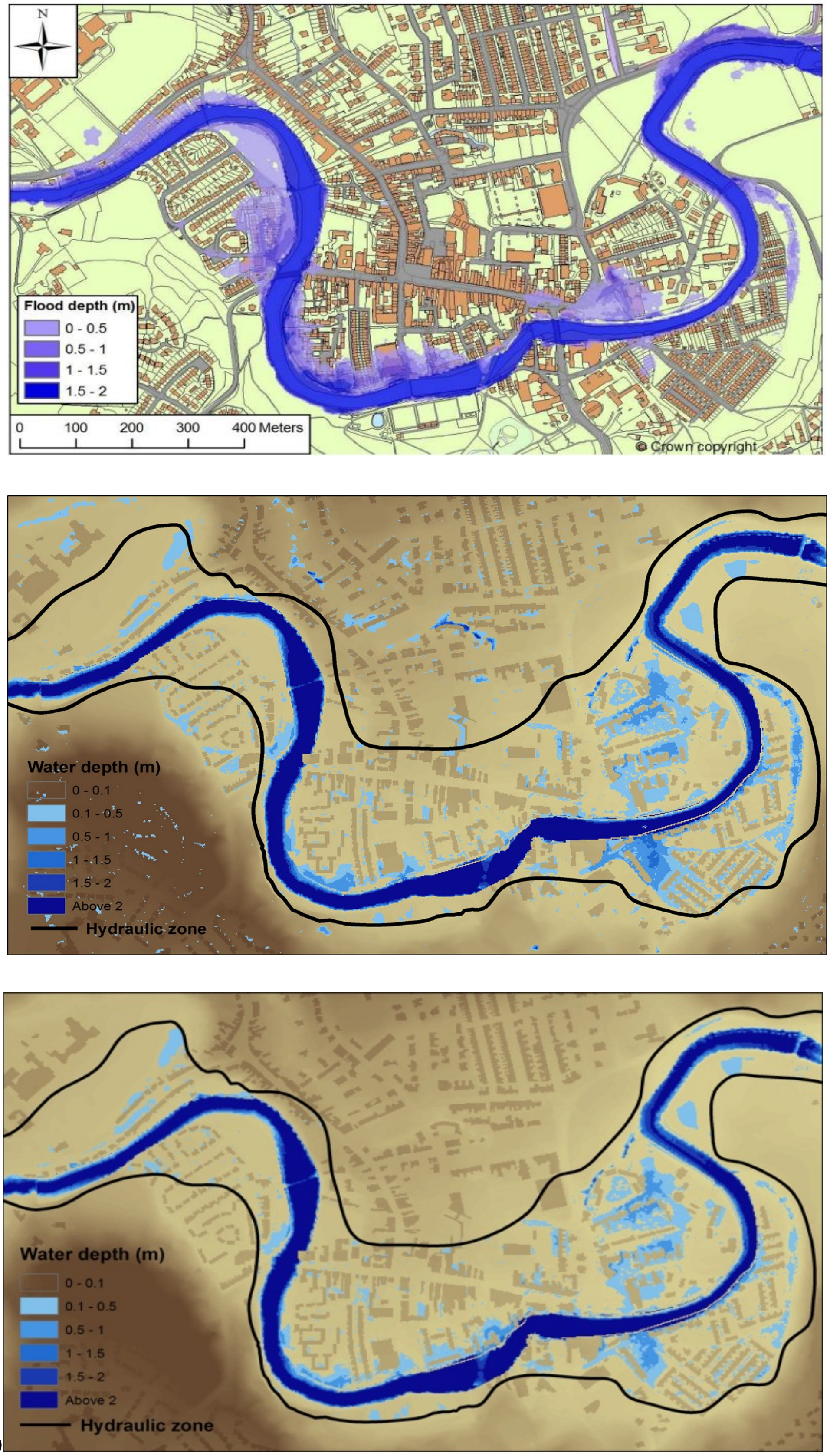


(a)

(b)

(c)

Figure 10 Inundation maps at 11am in the town centre: (a) post-event investigation (Parkin, 2010); (b) full 2D model; (c) coupled model.



(a)
(b)
(c)

Figure 11 Inundation maps at 1pm in the town centre: (a) post-event investigation (Parkin, 2010); (b) full 2D model; (c) coupled model.

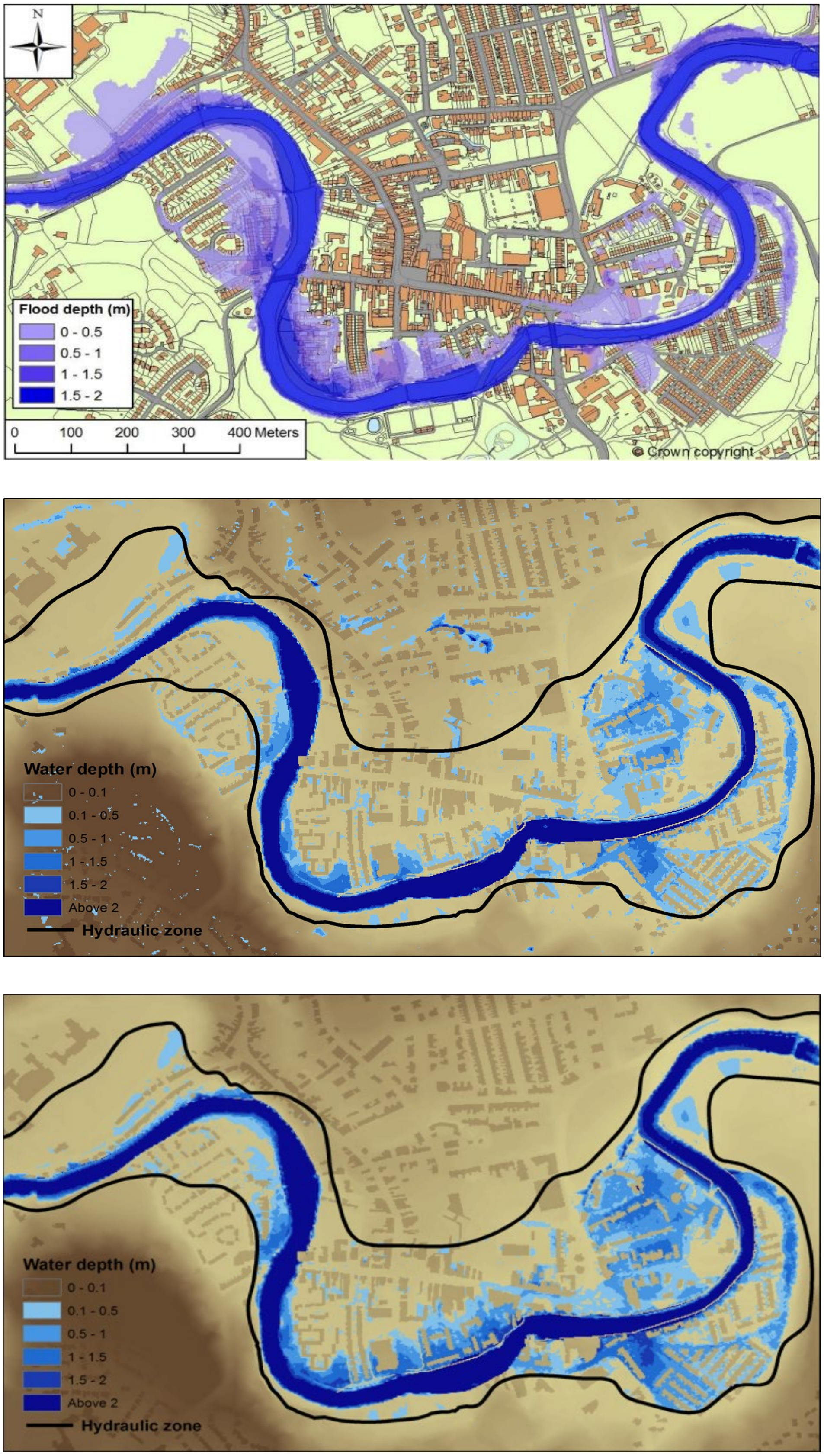
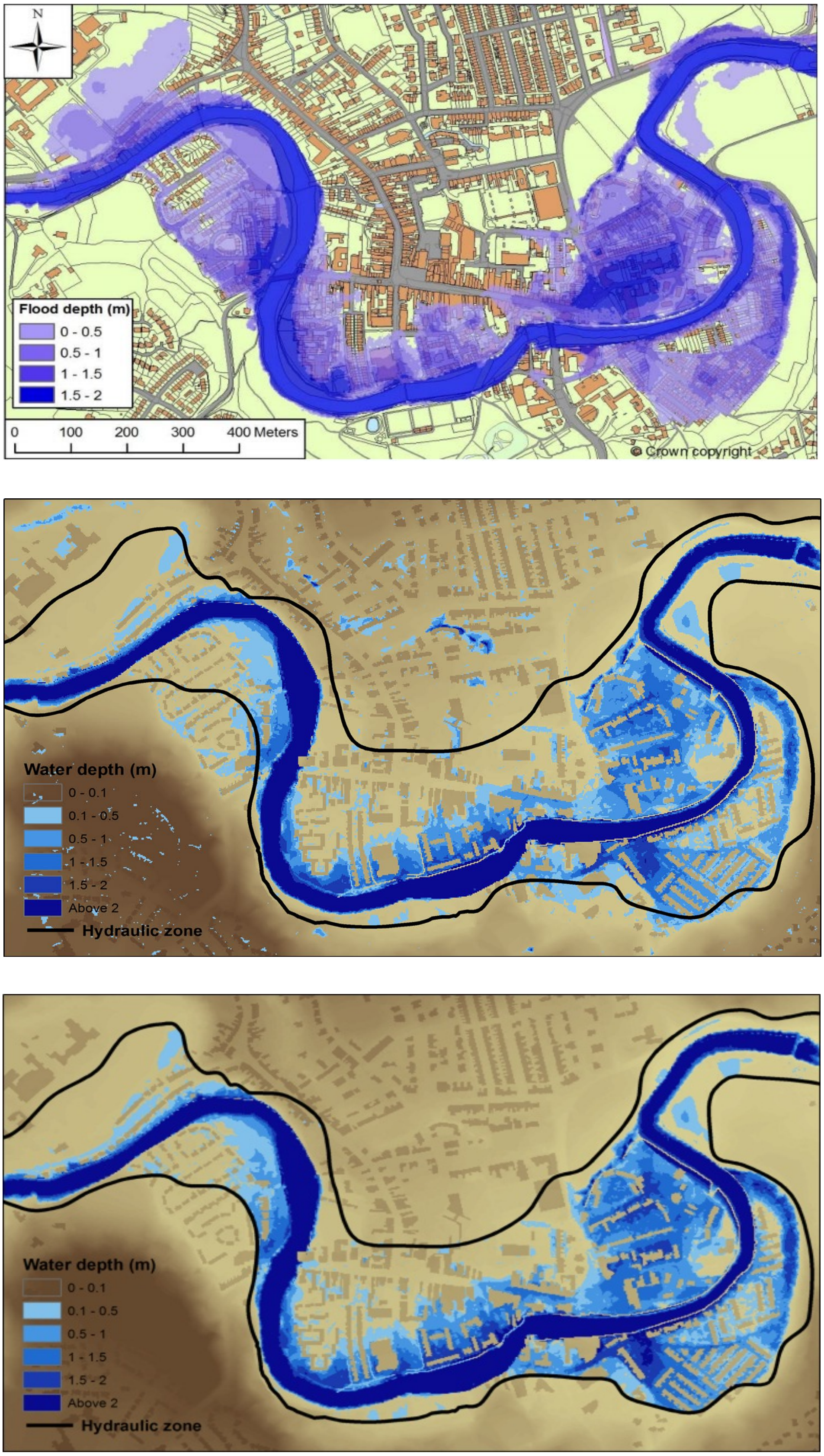
(a)
(b)
(c)


Figure 12 Inundation maps at 3pm in the town centre: (a) post-event investigation (Parkin, 2010); (b) full 2D model; (c) coupled model.



(a)

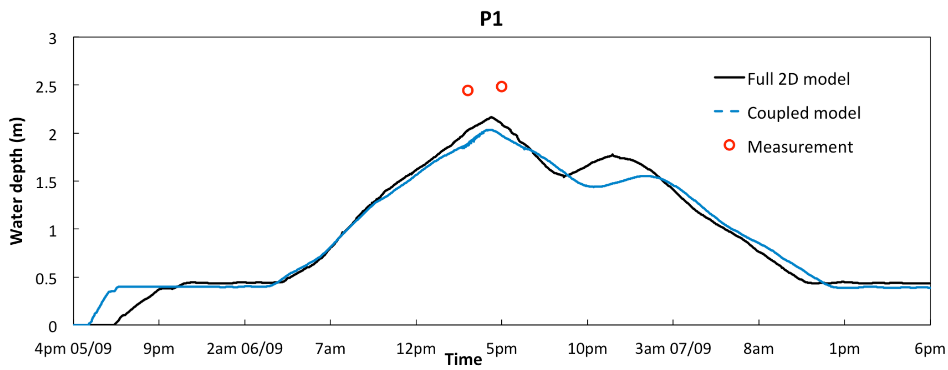
(b)

(c)

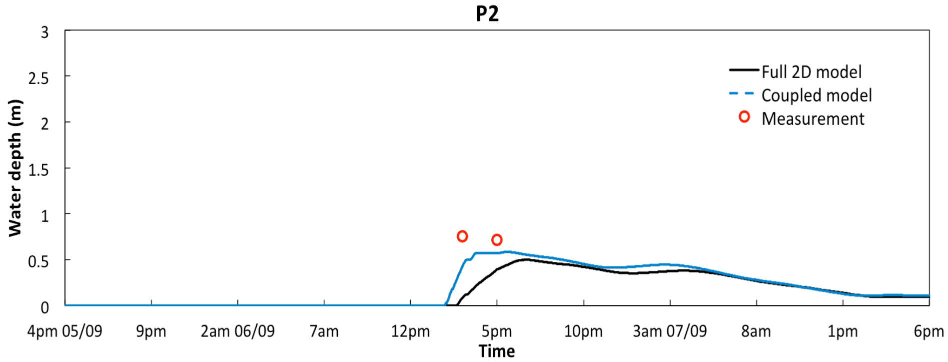
Figure 13 Inundation maps at 5pm in the town centre: (a) post-event investigation (Parkin, 2010); (b) full 2D model; (c) coupled model.

Water depths at the six critical points are recorded by both models and plotted in Figure 14. At all of the critical points, the water depths generally rise until reaching a peak, and then fall. After this, the water depths increase again to a second but lower peak before a final retreat of the flood water. The 'twin peak' shape of the water depth series reflects the similar shape of the inflow hydrograph, as shown in Figure 5. The water depths from the coupled model match reasonably well with those obtained by the full 2D shallow flow model in all of the critical points, particularly at P1, P4 and P6. However, deviations are seen in P2, P3 and P5, where the coupled model generally produces slightly larger depths than the full 2D shallow flow model. As a matter of fact, points P2, P3 and P5 are located relatively nearer to the zone border than the other critical points, and therefore more influenced by the lateral inflows from the hydrological zone. The faster routing method of 'unit hydrograph' may explain the larger depth as well as the earlier arrival time predicted by the coupled model. In practice, the use of slightly larger hydraulic zones is therefore recommended and may effectively minimise the effect.

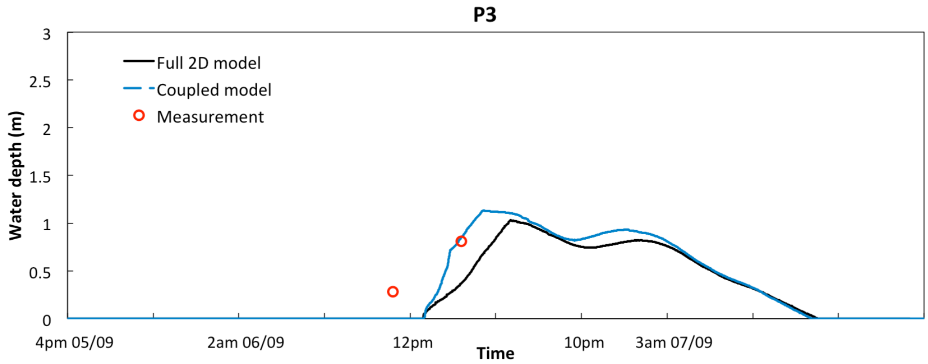
When compared with the measured water depths in the post-event investigation, obvious discrepancy can be found. Results from both models give shallower depth than the measured data at P1 and P2 but deeper depth at P6. The full 2D shallow flow model performs better at P3 and P5, while the coupled model behaves better at P4. Negating elements of the draining process along with limitations of the crowd-sourced observation data may explain these differences. As a whole, the results from the two models are considered to be consistent and the coupled model is preferable for wider applications due to its high computational efficiency whilst maintaining satisfactory simulation accuracy.



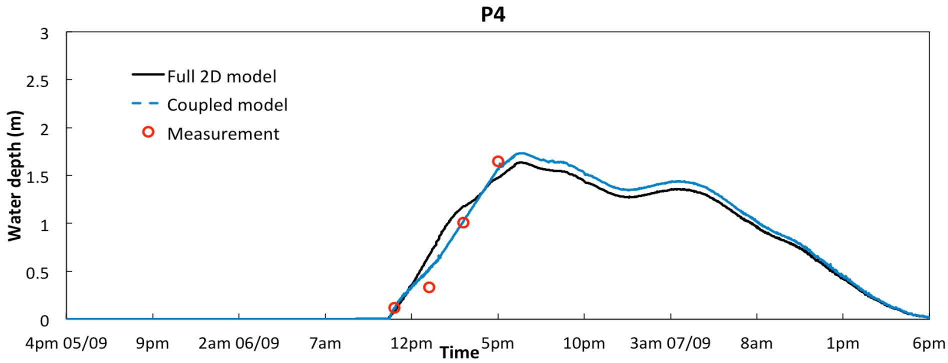
(a)


P2
Water depth (m)
3
2.5
2
1.5
1
0.5
0
Full 2D model
Coupled model
Measurement
4pm 05/09
9pm
2am 06/09
7am
12pm
5pm
10pm
3am 07/09
8am
1pm
6pm
Time

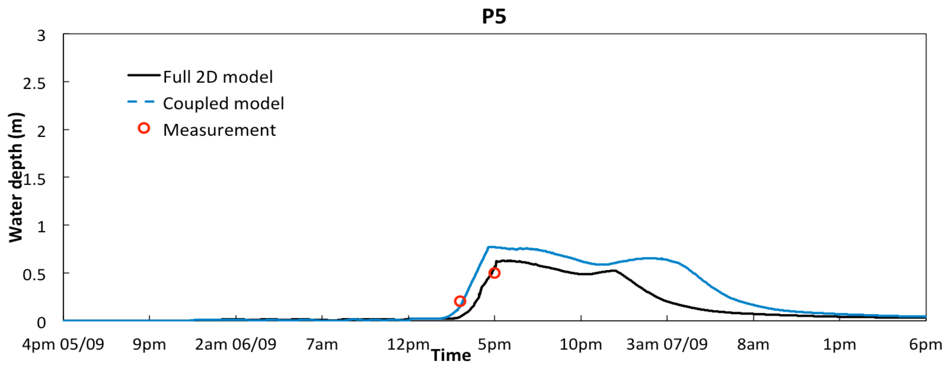
(b)


P3
Water depth (m)
3
2.5
2
1.5
1
0.5
0
Full 2D model
Coupled model
Measurement
4pm 05/09
2am 06/09
12pm
Time
10pm
3am 07/09

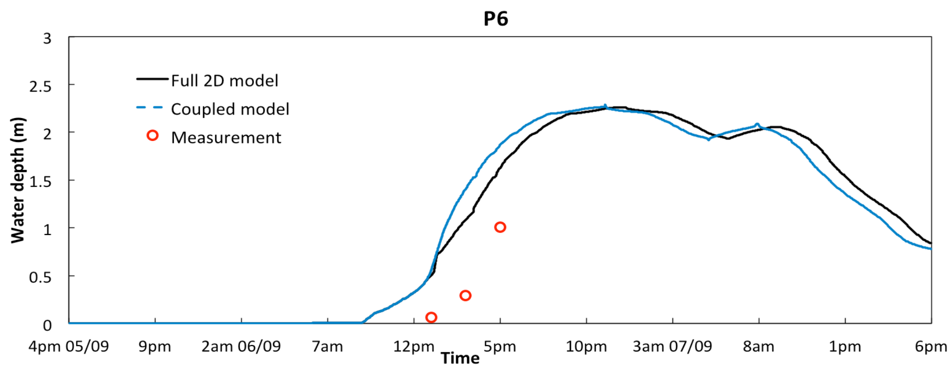
(c)


P4
Water depth (m)
3
2.5
2
1.5
1
0.5
0
Full 2D model
Coupled model
Measurement
4pm 05/09
9pm
2am 06/09
7am
12pm
Time
5pm
10pm
3am 07/09
8am
1pm
6pm

(d)


P5
Water depth (m)
3
2.5
2
1.5
1
0.5
0
Full 2D model
Coupled model
Measurement
4pm 05/09
9pm
2am 06/09
7am
12pm
Time
5pm
10pm
3am 07/09
8am
1pm
6pm

(e)



(f)

Figure 14 Time histories of water depth at the critical points in the town centre.

In terms of model performance, the coupled model costs 175.2 hours of CPU time to complete the simulation, while the full 2D model takes 2137.4 hours. For this particular simulation, the coupled model is therefore 12.2 times computationally more efficient, i.e. the computational efficiency has been dramatically improved by the coupled model, against the full 2D shallow flow model for the same simulation without significantly compromising the simulation accuracy. This improved simulation efficiency is consistent with the use of much less computational cells for hydrodynamic calculation in the coupled model. As shown in Table 3, the full 2D simulation involves about 17 times more hydrodynamic computational cells than the coupled model. The model speedup is hence related to the size of hydrological zones and larger hydrological zones will clearly lead to more efficient simulations.

5. Conclusions

This paper presents a new coupled hydrodynamic and hydrological model for urban flood simulation including flow from upstream steep catchment areas. The model has the following features:

- The computational domain / catchment is divided into hydraulic and hydrological zones according to a design flood event to ensure flows only occur from hydrological zones to hydraulic zones and hence facilitate an effective one-way coupling method;
- A lumped conceptual hydrological model is used to improve computational efficiency as well as maintaining reasonable representation of hydrological processes;
- Overland flows into the hydraulic zone are estimated and distributed using a series of ‘unit hydrographs’ generated by pre-running a hydrodynamic model;
- Inside the hydraulic zone, hydrological processes caused by precipitation and soil infiltration are approximated using a lumped conceptual hydrological model and taken into account in the full 2D hydrodynamic model as external source terms.

The new coupled model has been successfully applied to reproduce a major flood event occurred in Morpeth, Northeast England in September 2008. The results are consistent and compare reasonably well with the numerical predictions obtained using a full 2D hydrodynamic model and also the post-event investigation data. For the simulations conducted in this work, the coupled model is over 10 times computationally more efficient than the full 2D model when conducting the same simulation with similar prediction accuracy. The current coupled model therefore provides a more efficient simulation tool for large-scale high-resolution flood simulation.

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References

Anselmo, V., Galeati, G., Palmieri, S., Rossi, U. and Todini, E. (1996) 'Flood risk assessment using an integrated hydrological and hydraulic modelling approach: a case study', *Journal of Hydrology*, 175(1-4), pp. 533-554.

Bonnifait, L., Delrieu, G., Lay, M.L., Boudevillain, B., Masson, A., Belleudy, P., Gaume, E. and Saulnier, G.M. (2009) 'Distributed hydrologic and hydraulic modelling with radar rainfall input: Reconstruction of the 8-9 September 2002 catastrophic flood event in the Gard region, France', *Advances in Water Resources*, 32(7), pp. 1077-1089.

Bravo, J., Allasia, D., Paz, A., Collischonn, W. and Tucci, C. (2012) 'Coupled hydrologic-hydraulic modeling of the upper Paraguay River basin', *Journal of Hydrologic Engineering*, 17(5), pp. 635-646.

CEH (2018) *National River Flow Archive: 22007-Wansbeck at Mitford*. Available at: http://www.ceh.ac.uk/data/nrfa/data/station.html?22007 (Accessed: 02/06/2018).

Coolgeology (2018) *Morpeth floods of 2008*. Available at: http://www.coolgeography.co.uk/GCSE/AQA/Water%20on%20the%20Land/Morpeth/Morpeth.htm (Accessed: 02/06/2018).

Correia, F.N., Rego, F.C., Saraiva, M.D.G. and Ramos, I. (1998) 'Coupling GIS with hydrologic and hydraulic flood modelling', *Water Resources Management*, 12(3), pp. 229-249.

Environment Agency (2005) *Wansbeck and Blyth Catchment flood management plan*. Bristol, UK.

Environment Agency (2009a) *Flooding in England: A national assessment of flood risk*. Bristol, UK.

Environment Agency (2009b) *Wansbeck and Blyth Catchment flood management plan*. Leeds, UK.

Environment Agency (2011) *Work continues to cut Morpeth flood risk, September 2010.* Available at: www.environment-agency.gov.uk/news/123207.aspx?month=9&year=2010&coverage=North+East (Accessed: 29/06/2011).

Evans, E., Ashley, R., Hall, J., Penning-Rowsell, E., Sayers, P., Thome, C. and Watkinson, A. (2004) *Foresight: Future flooding Volume II: Managing future risks*. London, UK.

Green, W. H., & Ampt, G. A. (1911). Studies on Soil Phyics. The Journal of Agricultural Science, 4(1), 1-24.

Gül, G.O., Harmancioğlu, N. and Gül, A. (2010) 'A combined hydrologic and hydraulic modeling approach for testing efficiency of structural flood control measures', *Natural Hazards*, 54(2), pp. 245-260.

Hunter, N.M., Bates, P.D., Horritt, M.S. and Wilson, M.D. (2007) 'Simple spatially-distributed models for predicting flood inundation: A review', *Geomorphology*, 90(3-4), pp. 208-225.

JBA Consulting (2008) *Castle Morpeth Borough Council: Flooding in Castle Morpeth 6 & 7 September 2008: Independent Review*. Northampton, UK.

Kim, J., Warnock, A., Ivanov, V.Y. and Katopodes, N.D. (2012) 'Coupled modeling of hydrologic and hydrodynamic processes including overland and channel flow', *Advances in Water Resources*, 37, pp. 104-126.

Kjeldsen, T.R. (2007b) *Flood Estimation Handbook. Supplementary Report No.1*. Wallingford, UK: Centre for Ecology and Hydrology.

Lastra, J., Fernández, E., Díez-Herrero, A. and Marquínez, J. (2008) 'Flood hazard delineation combining geomorphological and hydrological methods: An example in the Northern Iberian Peninsula', *Natural Hazards*, 45(2), pp. 277-293.

Lerat, J., Perrin, C., Andréassian, V., Loumagne, C. and Ribstein, P. (2012) 'Towards robust methods to couple lumped rainfall-runoff models and hydraulic models: A sensitivity analysis on the Illinois River', *Journal of Hydrology*, 418-419, pp. 123-135.

Lian, Y., Chan, I.C., Singh, J., Demissie, M., Knapp, V. and Xie, H. (2007) 'Coupling of hydrologic and hydraulic models for the Illinois River Basin', *Journal of Hydrology*, 344(3-4), pp. 210-222.

Liang, Q. (2010) 'Flood simulation using a well-balanced shallow flow model', *Journal of Hydraulic Engineering*, 136(9), pp. 669-675.

Liang, Q. and Borthwick, A.G.L. (2009) 'Adaptive quadtree simulation of shallow flows with wet-dry fronts over complex topography', *Computers and Fluids*, 38(2), pp. 221-234.

Marsh, T.J. and Hannaford, J. (2007) *The summer 2007 floods in England and Wales - a hydrological appraisal*. Wallingford, U.K.

Mejia, A.I. and Reed, S.M. (2011) 'Evaluating the effects of parameterized cross section shapes and simplified routing with a coupled distributed hydrologic and hydraulic model', *Journal of Hydrology*, 409(1-2), pp. 512-524.

Met Office (2008a) *Heavy rainfall early Septembe 2008*. Available at: http://www.metoffice.gov.uk/climate/uk/interesting/sep2008/ (Accessed: 02/06/2018).

Met Office (2014) *The Recent Storms and Floods in the UK*. Exeter, UK.

Morita, M. and Yen, B.C. (2002) 'Modeling of conjunctive two-dimensional surface-three-dimensional subsurface flows', *Journal of Hydraulic Engineering*, 128(2), pp. 184-200.

Paiva, R.C.D., Collischonn, W. and Tucci, C.E.M. (2011) 'Large scale hydrologic and hydrodynamic modeling using limited data and a GIS based approach', *Journal of Hydrology*, 406(3-4), pp. 170-181.

Parkin, G. (2010) *The September 2008 Morpeth flood: Information gathering for dynamic flood reconstruction.* Newcastle upon Tyne: Newcastle University.

Penning-Rowsell, E., Viavattene, C., Pardoe, J., Chatterton, J., Parker, D. and Morris, J. (2010) The benefits of flood and coastal risk management: A handbook of assessment techniques. London: Flood Hazard Research Centre.

Pitt, M. (2008) *The Pitt Review: lessons learned from the 2007 floods*. London, UK.

Rawls, W.J., Brakensiek, C.L. and Saxton, K.E. (1982) 'Estimation of soil water properties', *Transactions - American Society of Agricultural Engineers*, 25(5), pp. 1316-1320, 1328.

Rawls, W.J. and Brakensiek, D.L. (1985) 'Prediction of soil water properties for hydrologic modelling', *Proceeding of Symposium on Wathershed Management in the Eighties*, pp. 293-299.

Shepard, D. (1968) 'Two-dimensional interpolation function for irregularly-spaced data', *Proceeding of 23rd ACM National Conference*, pp. 517-524.

Thompson, J. (2004) 'Simulation of wetland water-level manipulation using coupled hydrological/hydraulic modeling', *Physical Geography*, 25(1), pp. 39-67.

VICAIRE (2006) *Engineering Hydrology*. Available at: http://echo2.epfl.ch/VICAIRE/mod_1b/chapt_10/main.htm (Accessed: 02/06/2018).

Walker, G.R. and Zhang, L. (2002) 'Plot scale models and their application to recharge studies', in Walker, G.R. and Zhang, L. (eds.) *Studies in Catchment Hydrology: the basics of recharge and discharge.* Melbourne, Australia: CSIRO.

Whiteaker, T.L., Robayo, O., Maidment, D.R. and Obenour, D. (2006) 'From a NEXRAD rainfall map to a flood inundation map', *Journal of Hydrologic Engineering*, 11(1), pp. 37-45.