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A. P. Hurford, C. Maksimovi and J. Leitão

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URBAN PLUVIAL FLOODING IN JAKARTA: APPLYING STATE-OF-THE-ART TECHNOLOGY IN A DATA SCARCE ENVIRONMENT

A. P. Hurfor[1] Č. Maksimović[2] and J. Leitão[2]

[1] HR Wallingford, Howbery Park, Wallingford, Oxfordshire, OX10 8BA, UK
(E-mail: a.hurford@hrwallingford.co.uk)
[2] Department of Civil and Environmental Engineering, Imperial College London, SW7 2AZ, UK
(E-mail: c.maksimovic@imperial.ac.uk; j.leitao05@imperial.ac.uk)

KEY WORDS

1D, 1D/2D, data scarcity, Jakarta, pluvial flooding, urban drainage

ABSTRACT

Available data relating to major pluvial flooding events in Jakarta, Indonesia were used to investigate the suitability of two different levels of sophistication in urban modelling tools for modelling these events. InfoWorks CS v9.0 was employed to build 1D and 1D/2D models of a 541ha area of inner city Ciliwung River catchment which has a history of being particularly badly affected by flooding during heavy rainfall events. The study demonstrated that a 1D model was sufficient to simulate the flood extent of a major event using the limited data available. While the 1D/2D model also performed well, more data and time would have been required to match the 1D model's simulation of flood extent. Much more detailed data would have been required to produce reliable results in the 1D/2D model and to enable any kind of verification or calibration of the two models beyond visual comparison with crude flood extent maps.

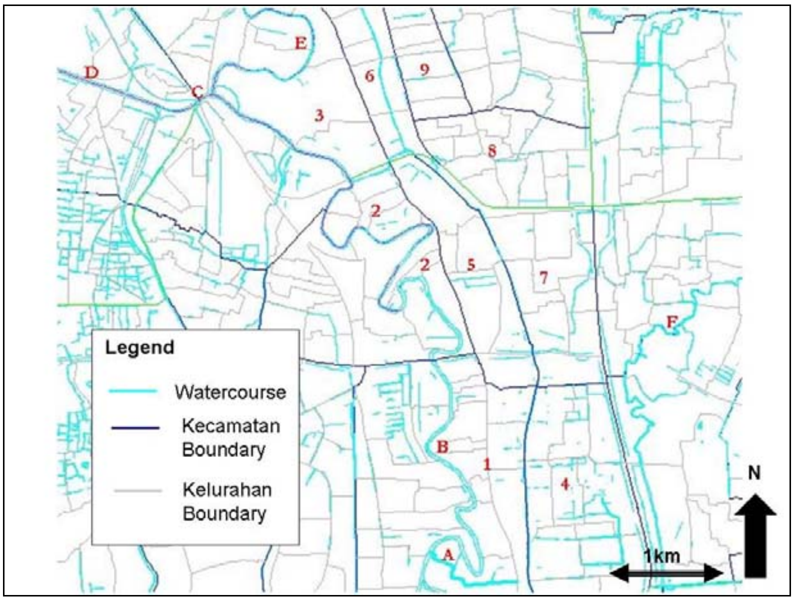
INTRODUCTION

This work aimed to assess the level of sophistication of urban drainage model suitable for modelling pluvial flooding in a developing country context. Jakarta is a typical example of an Asian mega-city suffering from all the classic problems of urbanisation in developing countries, including the flooding analysed here. The city has grown at an explosive rate, with encroachment on the floodplains of the numerous rivers rife.

Through consultation with local partners and considering the availability of data, a 541ha area of inner city Ciliwung River catchment was selected for investigation in this study. Figure 1 shows the extent of this area with the Ciliwung River running northwards then north-westwards from centre bottom.

Only an open channel storm drainage system exists in the vast majority of the city. It is of limited extent and has failed to keep pace with rapid urbanisation since initial construction in the Dutch colonial era (Caljouw *et al*., 2005). The humid tropical climate provides regular high intensity and high volume rainfall events showing a strongly seasonal pattern. This often leads to flooding with significant economic, health and social impacts.

Large scale dredging and canalisation work was recommended in the past as the solution to urban flooding in Jakarta. This is now seen as inappropriate and impossible to sustain so stormwater management techniques have been proposed (NIPPON KOEI & Kwarsa Hexagon, 2005).



A) Bidaracina Ruangan Warga (RW) 06
B) Bidaracina RW 014
C) **Manggarai Flood Gates**
D) **Western Flood Canal**
E) **Lower Ciliwung River**
F) Cipinang River

1) Kel. Bidaracina, Kec. Jatinegara
2) Kel. Kampung Melayu, Kec. Jatinegara
3) Kel. Kebun Manggis, Kec. Matraman
4) Kel. Cipinangcempedak, Kec. Jatinegara
5) Kel. Balimester, Kec. Jatinegara
6) Kel. Palmeriam, Kec. Matraman
7)Kel. Rawabunga, Kec. Jatinegara
8) Kel. Pisangan, Kec. Matraman
9) Kel. Kayumanis, Kec. Matraman

Figure 1 Map of study area showing administrative boundaries and water bodies. Only numbered villages named to right of figure included in model (source: BAKOSURTANAL)

Modelling is often proposed as the best way to investigate the physical processes occurring and propose control measures for urban flooding. Considering the quality and availability of relevant data, particularly in developing countries, the impacts of assumptions made during modelling can call into question the validity of the results. As modelling sophistication increases, the data required to drive the models and provide meaningful results increases in both quantity and quality. Typical cutting-edge models in the developed world would use 5 minute rainfall intensity data and high resolution LiDAR survey topographical data to enable the accurate delineation of surface flow pathways. This study compared 1D and 1D/2D models to investigate which level of complexity is best suited to a relatively data scarce urban environment such as that found in Jakarta in 2008.

METHODS

Model Building

Digital Terrain Model (DTM) and Digital Elevation Model (DEM) creation. A 1x1m resolution DTM was created by interpolating data points extracted from a 1:5000 scale engineering survey map obtained from the Indonesian government's national survey and mapping agency (BAKOSURTANAL). Contour lines were available at one-metre intervals and converted to point elevations to combine with spot heights for ease of interpolation. This DTM formed the basis of the 2D mesh surface in the 1D/2D model as well as the ground model across which to interpolate flood levels in the 1D model. Furthermore, this ground model was used to infer the invert levels of the open channel drainage system.

A DEM was also created, with the aim of representing flow pathways around buildings. The buildings layer taken from the BAKOSURTANAL map was simplified and aggregated repeatedly to simplify what was initially an extremely complex layer. Once this process was complete, the layer was added to the DTM at a constant height of 3m to provide relief from the surrounding terrain.

Drainage network modelling. The drainage system in the study area is comprised entirely of open channels and two separate maps (from the Jakarta Public Works department and from BAKOSURTANAL) were used to approximate its extent despite inconsistencies. A hierarchy of three standard trapezoidal channel cross-sections (ranging from 500(w)x600(h)mm to 2000(w)x3000(h)mm) were assumed, although the channels are unlikely to be so regular in reality due to inconsistent construction.

Based on the DTM, GIS techniques were used to delineate 217 subcatchments draining to the model's open channels. The runoff from each subcatchment was applied to the upstream manhole of the corresponding channel. Manholes were only used to connect junctions of open channels and the plan area of the manholes was calculated to ensure no unrealistic provision of storage in the network.

Large portions of the study area lying adjacent to the river appeared from the available data to be unserved by any built drainage system. Links representing the river were used to create subcatchments as described above and those unserved by the drainage system were given overland flow channels modelled roughly to the dimensions of a narrow paved road, flowing directly to the river.

Representation of the Ciliwung River. The 1D network was characterised by the absence of links representing the Ciliwung River itself in the model network. Outfall nodes were created at the downstream ends of the drainage network where it met the river, enabling level files to be applied to the appropriate outfalls to mimic the backwater effects of high river stages.

The 1D model made use of the hourly Automatic Water Level Recorder (AWLR) stage data obtained from the gauging data at the Manggarai flood gates which formed the downstream extent of the model. Where automatically recorded data were not available, manually recorded stage data were used. A correlation was carried out between manual and AWLR data for the 2007 flood event period – Excel's CORREL function giving a value of 0.993 indicating that both datasets were of similar quality, if not accuracy. These stage data were applied as level files to each outfall from the storm drainage system to the river without variation for increased elevation upstream. The river reach included in the model was around 5km in length, but the DTM showed the change in elevation to be as little as 3 – 4 metres. The downstream-most end of the storm drainage network modelled actually discharges into the Lower Ciliwung River which is connected to the Ciliwung via a second set of flood gates different from those which control flow into the Western Flood Canal. The levels applied to the outfalls in this section were taken from the manually recorded stage data from downstream of the Lower Ciliwung flood gates. Again, no adjustment was made for change in bed elevation.

The integrated 1D/2D network by contrast, included InfoWorks CS (IWCS) river links to represent the river channel. The minimum bed elevation of a typical engineering survey cross-section near the middle of the river reach considered by this study was examined and compared to the DTM channel elevation at the same location. A discrepancy of approximately 1.5m was noted – the survey showing a lower elevation than the DTM. On this basis, it was considered reasonable to represent the river as a standard trapezoidal channel sitting below the DTM. This was achieved by creating manhole nodes of 50m2 shaft and chamber cross-section at the lowest points in the DTM river channel near each outfall (from both drainage network and overland flow routings). The elevation of the ground level for each manhole was added using the inference tool in IWCS to ensure that if flooding took place, it would flow between the manhole and the mesh of the 2D simulation polygon at the correct depth. The assumption implicit at this stage was that the DTM accurately represented the river channel above the dry weather flow depth. The BAKOSURTANAL map topography data did not seem to define a distinctive channel for low flows within the greater river channel so it was considered appropriate to utilise the existing river channel data to contain flood waters to a certain extent. As simulated water could only enter or leave the river link via the manholes, and the water would collect in the river channel before finding a manhole to enter, this was deemed a good approximation of the physical processes.

The representation of the river in the 1D/2D model was significantly more complex to use in terms of data input: as level files can only be applied to outfalls in v9.0 of IWCS, it was necessary to use different methods of mimicking the levels in the river and their effects on flooding in the integrated 1D/2D model. Two approaches were taken to ensure the river did not start ‘dry’ at the beginning of the simulation:

1) Applying an inflow to the first (furthest upstream) links of the two rivers (Ciliwung and Lower Ciliwung) and two drainage network channels which connect to the upstream catchment. A simulation was then run for 24 hours with no rainfall to allow a stable level of water to accumulate in the channels. The final state of this simulation without rainfall was then saved as a simulation state which was used as the initial simulation conditions of runs considering the impacts of river levels.

2) The stage data from the Manggarai gauging station were used to create a level file for the upstream node of each river link. Level files could only be applied to outfalls, so an outfall was added outside of the 2D simulation polygon at the same ground level as the river node and connected to it with a link of the same dimensions as the rest of the river. The level files generated flow in the river links by imposing a water level above datum and above the base of the river link. Level files were adjusted for the difference in elevation of each river node from the stage measurement point. Similar to the inflows above, a simulation state file was created by running a simulation with only level files and no rainfall for 48 hours.

In running both of these variants of the 1D/2D network, the level files or inflows which created the simulation state file were also applied to the simulation, to maintain the initial levels established as described above.

Creation of flood compartments (1D model). Flood compartments needed to be defined in the IWCS 1D model across which manhole node flood levels could be interpolated to give a representation of flood extent. It was found that the most realistic representation of flood extent was produced when a single flood compartment was defined around the whole study area and each of the manhole nodes was defined as a flood point within that compartment. In this way the flooding from each node was interpolated with an inverse distance weighting across the whole study area. The DEM was used as the ground model for this interpolation so the flood levels were displayed as surrounding the buildings unless flood levels exceeded the standard 3m building height in the DEM. All manhole nodes in the 1D model were set to *stored* type, meaning that any flood water from a node is stored in a cone-shaped virtual reservoir and returns to this node as the flood level drops.

2D Mesh creation (1D/2D model). The mesh used to convey 2D flows was created in IWCS using the built-in function. The maximum triangle size was limited to 1000m2 to balance the need for resolution from the ground model with reasonable computation times. Despite extensive work to simplify and aggregate the buildings layer obtained from the BAKOSURTANAL survey maps, it proved extremely difficult to represent the complex arrangements of buildings in the 2D mesh so these were omitted.

Input data

The Ciliwung River’s catchment management authority (BBSWCC) was able to provide data from their automatic rainfall and river stage gauging station at the downstream end of the study area – the Manggarai flood gates. These were applied as rainfall and level files to the model assuming that the river stage was relative to the same datum as the contour data used to produce the DTM. River stage data were also available for the upstream extent of the study area but it proved difficult to ascertain the relationship between the local datum used and the standard datum to the North East of Jakarta.

The maximum resolution of available rainfall data was 1 hour although the gauges were said to record every 15 minutes. Although tools were available, no attempt was made to disaggregate this to a finer timescale as no higher resolution data were available against which to calibrate any disaggregated data.

Rainfall data from the Automatic Rainfall Recorder (ARR) were provided as a 24 hour moving-sum due to the system being part of a flood warning system – 24 hour accumulations being considered strong indicators of flooding. These data were examined to identify the peak 24 hour intensities thought likely to cause the most significant pluvial flood events (see Fig. 2). Four events were identified above a threshold of 150mm and considered most useful for modelling.

The rainfall records around these peak values were extracted from the data from the onset of each storm for application in the model. A disaggregation algorithm was applied in order to obtain hourly totals from the 24 hr accumulation totals although this suffered from uncertainties at the beginning of the datasets. Two of these events corresponded to known historical flood events in the area confirming the relationship between heavy local rainfall and flooding.

Hourly rainfall data were also available from a manual recording using a Hillmann device at the Indonesian Meteorology and Geophysics Agency (BMG) in Jakarta, around 6km North of the Manggarai flood gates. These were a useful comparison allowing the sensitivity of the model to rainfall intensities to be tested using rainfall from the same periods.

Both the 1D and 1D/2D models were subject to the same issue of including drainage channels which connect to upstream parts of the Ciliwung catchment. This required inflows to be included in the model in order to ensure these channels did not start 'dry' where they would in reality be carrying flows from the upstream catchment. Assumptions were made about appropriate inflow rates to apply due to a lack of available data.

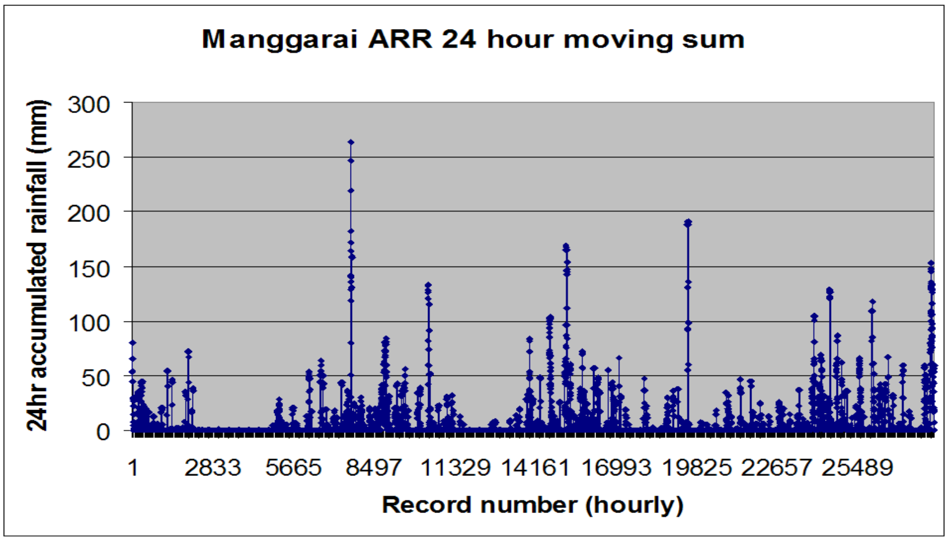


Figure 2 Plot of 24-hour rainfall accumulations from the ARR at Manggarai

Model simulations

The ability of the models to reproduce conditions for which observed flood extent data were available in conjunction with model input data (the major 2002 and 2007 events) was tested initially. Both the 1D and 1D/2D models were run with identical input data. The 1D/2D model was also run with networks with inflows applied to the rivers and drainage channels as described above. Inflows were adjusted to provide a simulation state file which produced subsequent simulation results closest to the observed flood extent data.

The response of the 1D model to different rainfall events as identified from the ARR data (Fig. 2) was tested by applying them with corresponding AWLR stage data. It was not practical to generate all the input files required to test each event in the 1D/2D model.

Sensitivity analysis. Within the rainfall files, it was possible to adjust parameters, such as the Urban Catchment Wetness Index (UCWI) value and evaporation rates. In order to test the sensitivity of results to these input parameters, the December 2003 event was used (due to having a short duration, practical for multiple simulation runs and including a particularly high peak of 127mm/hr) with both the 1D and 1D/2D models and the parameters changed. The alternative UCWI was set to 100, from the default value of 50 and the evaporation rate was also doubled from 5mm/day to 10mm/day. Each parameter was adjusted in isolation to discern its individual effects, while a run was also performed with both adjustments to investigate any combined effect.

It was recognised that the assumed drainage channel dimensions, along with the extent of the network, could have a significant impact on the amount of pluvial flooding which occurred in the simulations. Rather than increasing the extent of the drainage system without any data to base this on, the dimensions of the small and medium sized channels were reduced by 50%. As the width, at least, of the major channels, had been corroborated by evidence from satellite imagery, these were left unchanged.

As assumptions were also made concerning the land use within model subcatchments, these assumptions were challenged by running the model with two changed proportions of road, roof and pervious area.

The models were not validated as such, but a range of runs with different rainfall events and associated level files where appropriate, acted as confirmation that the model was stable and not producing unpredictable results when faced with inputs other than those which acted as the focus, namely the 2002, 2007 and December 2003 events.

RESULTS AND DISCUSSION

Flood extent data were only available for the 2002 and 2007 flood events in the study area. These data were obtained from the Public Works department, the resolution recorded for the 2007 event being superior.

Due to the low resolution in the observed flood extent data from 2002 (see Fig. 3a), it was only considered worthwhile to compare model simulation outputs to the January/February 2007 (Fig. 3b) flood extent. Simulation results suggested that the flooding events had been coincidental rather than purely fluvial or pluvial; in both 1D and 1D/2D models it was necessary to account for both fluvial and pluvial processes to obtain the best flood extent reproduction.

A good reproduction of the 2007 flood extent was achieved using the 1D model (Fig. 3c) despite the relatively crude method used to display flood extent. The best reproduction of flood extent achieved with the 1D/2D model (Fig. 3d).was not as good as the 1D model. This was considered to be due in large part to the greater complexity required to represent the downstream boundaries of the study area.

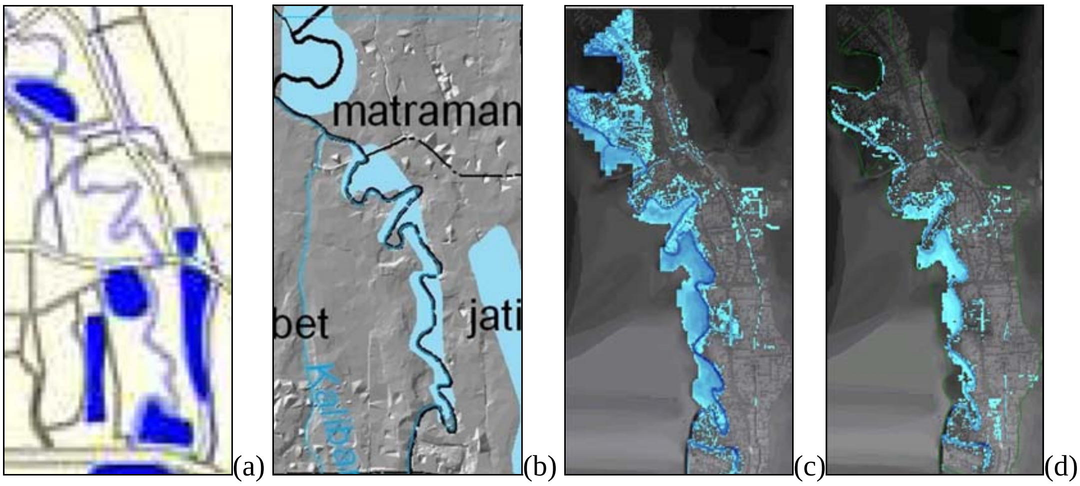


Figure 3 Flood extent maps (a) Observed 2002 event (source: Public Works) (b) Observed 2007 event (source: Public Works) (c) simulated extent using 1D model (d) simulated extent using 1D/2D model

Flood depths in both the 1D and 1D/2D model simulations were broadly representative of those described by reports of flooding, but the focus here has been on flood extent, as the data are more qualitative and do not include depths.

The biggest area of discrepancy between the 2007 flood map and the 1D/2D simulated extent is at the downstream end of the catchment (top left of maps). This is likely to be due to difficulties in regulating the flow out of the model which could only occur through the final manhole linked to an outfall. The physical reality is that two sets of sluice gates control flow from the Ciliwung into the Lower Ciliwung and the Western Flood Canal. The Western Flood Canal has a flow capacity of around 370m3/s and the hydraulic capacity of the Lower Ciliwung is much lower. Flow is much more highly regulated in the Lower Ciliwung as it flows through the centre of the city, in the vicinity of the presidential palace (Caljouw *et al.*, 2004)

While data are available for the stage levels at both these control structures, without stage discharge curves, it is very difficult to estimate the flows occurring at these points. It is considered that with more time, it would be possible to calibrate the model. This could be done using the size of the manhole through which water drains to the network outfall at Manggarai, along with stage data. Such a calibration remained beyond the scope of this study.

Data from Jakarta provincial Public Works Department state that the total flooded area for the whole of East Jakarta in the 2007 event was 121.9 ha for a maximum duration of 48 hours and to a maximum depth of 3m at Kampung Melayu, (Fig. 1 village no. 2). East Jakarta is much bigger than the study area however at around 190 km2 (East Jakarta government, 2009). The maximum flood extents suggested by this study's 1D/2Dmodelling for this event cover a range between 40ha and 153ha depending on the input data. Results from1D modelling did not include flooded area and the maximum stored flood volume data which were produced were not considered conducive to comparison with available historical extent data.

While even the smallest of these areas look large in comparison with the Public Works' data, it must be noted that the maximum flooded area data includes around 80ha of the 2D mesh which are actually inside the river channel. Flooding in this area would not be considered flooding in reality.

The total simulation study area is 541 ha, which is approximately 3% of the areal extent of East Jakarta. Spatial variation due to factors such as the proximity to rivers etc. would make it inaccurate to simply scale down the expected flood extent value. No numerical data were available for flood extents in the study area.

Using numerical results concerning maximum flood extent did not facilitate direct analysis of how well a particular simulation represented observed flood extents. It was therefore considered that the best way to examine a particular simulation's reproduction of historical events was to visually compare simulated maximum extents with the low resolution historical extents available.

Pluvial type flooding

The nature of 1D flood mapping leads to water being displayed as flooding at the lowest points on the DTM, thereby failing to represent localised pluvial flooding. Furthermore, in both 1D and 1D/2D models, flooding only occurs from manhole nodes once water has accumulated in the system. This misses an important component of pluvial flooding – pooling of water before reaching a drainage pipe or channel. This could perhaps be rectified in part by using the function in later versions of IWCS to apply rainfall directly to the 2D mesh rather than to subcatchments.

The 1D/2D simulations were better at demonstrating the possibility of pluvial flooding away from the banks of the river. There are a number of areas where flood water accumulated in low areas of the DTM during the maximum flooding. Unfortunately, it was not possible to reflect the presence of buildings on the terrain, which may have altered the flood characteristics. It would not have been useful in comparing flood extents however, as the resolution of the historical data is too coarse to display these areas of pluvial flooding, whether they are realistic or not.

CONCLUSIONS

The study area is complex and relatively large for accurate modelling of this type and more detailed observed event data would be needed in order to calibrate the model better, such as:

- flow data for various points;
- more detailed data concerning the extent and dimensions of the drainage system;
- accurate and detailed flood extent data.

Both 1D and 1D/2D models indicated that flooding which occurred in 2007 was coincidental. Although the 1D model reproduced flood extent data more closely, particularly at the downstream boundaries, it is considered possible to match this with the 1D/2D model with more time and data available. Whether this would be a worthwhile pursuit, considering the low resolution of event data available to judge performance against remains questionable.

Only the 1D/2D model was also able to convincingly predict pluvial flooding away from the river and regardless of river flooding. The lack of detailed flood extent data meant the accuracy of this prediction could not be confirmed but the study indicates that this technology is better suited to the modelling of pluvial flooding. Furthermore, any modelling investigation of the hazard posed by pluvial flooding would need to utilise a 2D component in order to provide velocity data for the flood waters rather than simply their extent.

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HR Wallingford Ltd
Howbery Park
Wallingford
Oxfordshire OX10 8BA
UK

tel +44 (0)1491 835381
fax +44 (0)1491 832233
email info@hrwallingford.co.uk

www.hrwallingford.co.uk