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An analysis of the combined consequences of pluvial and fluvial flooding

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ABSTRACT

Intense rainfall in urban areas often generates both pluvial flooding due to the limited capacity of drainage systems, as well as fluvial flooding caused by deluges from river channels. The concurrence of pluvial and fluvial flooding can aggravate their (individual) potential damages. To analyse the impact caused by individual and composite type of flooding, the SIPSON/UIM model, an integrated 1D sewer and 2D overland flow was applied to numerical modelling. An event matrix of possible pluvial scenarios was combined with hypothetic overtopping and breaching situations to estimate the surface flooding consequences in the Stockbridge area, Keighley (Bradford, UK). The modelling results identified different flooding drivers in different parts of the study area and showed that the worst scenarios resulted from synthesised events.

KEYWORDS

Urban inundation; integrated modelling; pluvial and fluvial flooding; sewer drainage.

INTRODUCTION

The continuous downpour within a basin often causes huge floods around river channels, as well as localised flooding in urban areas. When torrent flushes into rivers and raises the water level, which exceeds the crest elevation of banks, the flow spills out of channels toward floodplains and results in fluvial flooding. On the other hand, modern cities usually rely on drainage systems to convey surface runoff produced by rainfall. Nevertheless, the design capacity restricts the maximum discharge that a drainage system can cope with such that pluvial flooding takes place when heavy storm occurs. The time scale and the flood magnitude of a fluvial event significantly differ from those of a pluvial event. The former typically lasts for days, or even weeks, and have widespread influences on floodplains along rivers. On the contrary, pluvial flooding seldom lasts for more than one day, and only affects local regions. To estimate the consequences of flooding in urban areas, integrated numerical models that include various system components are emerging to describe the flooding process more accurately. However, due to the above-mentioned distinction most studies usually focus on one of these two types of flooding and not on their combined effect.

For fluvial flood modelling, combined 1D channel and 2D overland flow models are widely applied to simulate flow dynamics between rivers and floodplains (Bradbrook et al., 2004; Horritt and Bates, 2002; Lin et al., 2006; Wongsa and Shimizu, 2001). Approaches of this type often route separately the flow in the river and the one on overland by solving 1D and 2D hydraulic equations, respectively, linking both components by weirs or pumps. The function of sewer drainage is often neglected. Regarding pluvial flooding studies, the 1D/1D dual drainage models were developed to simulate flow interactions among sub-catchments, and between the above ground and the below ground systems (Djordjević et al., 1999; Nasello and Tucciarelli, 2005). Natural flow paths and retention basins are regarded as the major drainage system for routing the surface flow, while sewer pipes, manholes and inlets are considered as the minor drainage system for conveying the sub-surface flow. Flow in both drainage systems is simulated by using a 1D hydraulic model and linked through manholes to reflect the bi-directional interactions between sub-surface and surface networks (Bolle et al., 2006; Leandro et al., 2007; Mark et al., 2004; Schmitt et al., 2005).

When the major drainage system capacity is insufficient to handle the excess runoff caused by pluvial events, the overland flow occurs. 1D surface flow modelling approaches are believed to be inadequate to model overland flow if this is no longer confined to predefined flow paths. 2D overland flow models are regarded to be a better tool to predict the movement of surface flows. Therefore, coupled 1D sewer and 2D inundation models, which consider the bi-directional flow interactions between sub- surface and surface flows, are applied to analyze details of overland flow propagations (Hsu et al., 2002; Thorndahl and Willems, 2008). Recently, commercial software such as SOBEK (WL|Delft Hydraulics, 2006), XP-SWMM 2D (Phillips et al., 2005) and MIKE FLOOD (DHI Water & Environment, 2006), also provide the integrated 1D sewer and 2D overland flow modelling function in their packages.

In reality, pluvial flooding frequently happens together with fluvial flooding, resulting in more severe consequences than the one caused by a single type of flooding (Ashley et al., 2005), in that case only an integrated dynamic model can assess all potential drivers and their combined effects (Balmforth et al., 2006). Although the primary risk may initially be perceived to be due to fluvial flooding, a diagnostic study covering pluvial flooding is required to highlight the influences of various flooding sources (Balmforth et al., 2006).

This study aims to analyse the composite situations of heavy rainfall and river flooding by numerical modelling. The flow interactions among channels, floodplains, and underground sewer networks are considered implicitly in the flood model. Flood defences along rivers and flap valves at drainage outlets are also taken into account for evaluating the effectiveness of countermeasures. Scenarios with various mixtures of river levels, rainfall intensities, and rainfall durations are simulated and compared. The study compares the contributions for various combined events to the consequences. The dominating flooding type of a study area is identified, which enables better understanding of detailed features for flood risk management. The procedures can also be applied to investigate different combinations of coastal, tidal, fluvial, pluvial and groundwater flooding.

METHODOLOGY

The study investigates the effects of pluvial and fluvial flooding and their combinations in urban area by using an integrated sub-surface/surface numerical model (SIPSON/UIM; Chen et al., 2007). The 1D sewer network model SIPSON (Djordjević et al., 2005) is used for calculating the rainfall-runoff hydrographs and the flow conditions in the drainage network, whereas the 2D overland flow model UIM (Chen et al., 2005) is employed for the surface flow simulation.

SIPSON consists of two components, the hydrological and the hydraulic models. The hydrological model (Radojković and Maksimović, 1984) computes the rainfall-runoff hydrographs of sub-catchments to be input as manhole inflows in the hydraulic model. The hydraulic model simulates the flow in drainage networks by simultaneously solving continuity equations for network manholes, energy equations for manholes and pipe/channel ends, the complete Saint Venant equations for flow in conduits and streets, and equations for other link types (pumps, weirs, etc.).

UIM is a 2-D non-inertia model derived from the St. Venant equations for overland flow simulations of alluvial plains with mild natural topography. The inertial terms are neglected by assuming the acceleration terms of water flow on the land surface are relatively small compared to

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gravitation and friction terms. The functions of hydraulic devices, such as pumping station, weir, orifice and gate, are also implemented by adopting the respective equations.

SIPSON/UIM model is coupled by discharge via manholes between sewer network and overland flow to reflect the rainfall-runoff processes in urban areas properly. The flood levels in river channels are used as the downstream conditions of the drainage outlet and overland boundaries. Weir equations are applied to calculate the overtopping/breaching discharge between river channel and overland surface.

RESULTS AND DISCUSSIONS

Study area

The paper uses the Stockbridge area (Figure 1) adjacent to the River Aire in Keighley (Bradford, UK) as case studies. The comprehensive records of flood events for model calibration and verification are not available although the area is known as flood prone. Figure 1 shows the satellite image and DTM with buildings of the study area, which is bounded by the River Aire and its tributary in the north and the east, respectively, Aire Valley Road (A650) in the south and Bradford Road (B6265) in the west.

Two main sewer pipes collect runoff from the north-west and the south-west upstream catchments and join in the area; joined by the local sewer network, the drainage system carries on towards the waste water treatment plant in the south-east, where a flap valve exists to prevent backwater from the river channel. The DTM with buildings was obtained from the LiDAR data, and resampled as 2m x 2m grid resolution for 2D overland flow modelling. The ground surface elevation varies from 83 m (areas next to the rivers) to 94 m (the roundabout in the west). The top elevation of levees along the River Aire was raised to 10 cm above 100 year flood level after a fluvial flooding event in 2000.

Figure 1. The satellite image (left, from Google Earth) and the DTM with buildings and sewer network (right) of Stockbridge area.

Both pluvial and fluvial flooding conditions and their combinations were simulated by the coupled SIPSON/UIM model. The numerical modelling results were integrated into a GIS database and an analysis toolbox was built to identify the dominant factor that causes inundation.

Pluvial flooding

Rainfall events with different return periods and durations were simulated in the study. Table 1 shows the rainfall intensity of the event matrix used for modelling. The frequency varies from 2 to 100 year return period and the duration ranges from 15 to 360 minutes. The flow discharge in river

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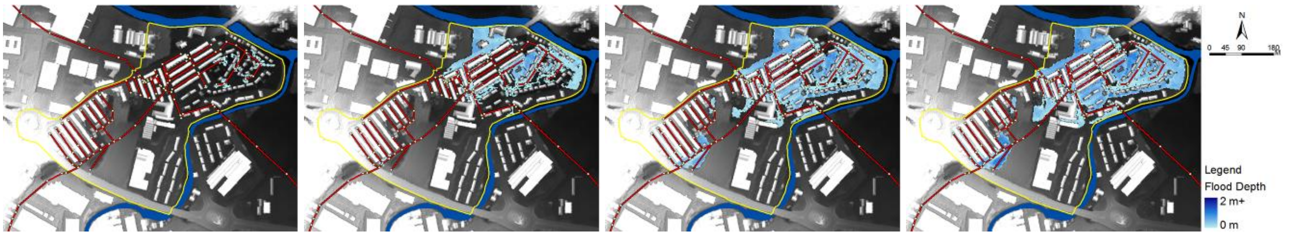
channels were assumed low such that the water levels did not affected the sewer drainage. Neither overtopping nor breaching of levees was considered during the simulations.

Table 1. Rainfall intensity (mm/hr) for a matrix of durations and return periods

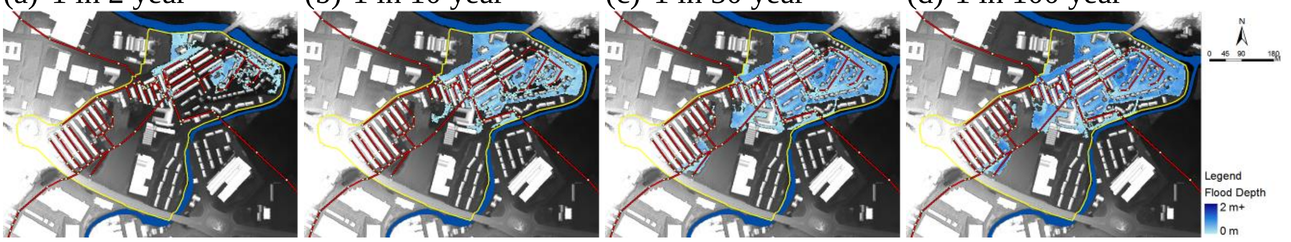
Duration	Return Period (year)						
(minutes)	2	5	10	20	30	50	100
15	27.92	40.84	53.48	67.44	76.84	91.72	115.68
30	18.12	26.00	33.58	41.86	47.38	56.06	69.92
60	11.75	16.54	21.08	25.99	29.23	34.28	42.26
120	7.62	10.53	13.24	16.14	18.03	20.96	25.54
180	5.91	8.08	10.08	12.21	13.59	15.71	19.02
360	3.84	5.14	6.33	7.58	8.38	9.61	11.50

Figure 2 shows the simulation results of 15- and 60-minutes rainfall events of different return periods. For the rainfall event with 1 in 2 year return period and 15-minutes duration, only few manholes were surcharged and the flooding was shallow and localised (Figure 2-(a)). The manholes on Beeches Road in the western areas began to surcharge when the rainfall intensity increased to 1 in 10 year return period (Figure 2-(b)), while the surcharge flow from manholes in the east part areas started propagating on the ground. The water depth raised by over 50 cm in the region between Cormwall Road and Worth Ave, and the region between B6265 and the north boundary.

For the 1 in 50 year return period rainfall, the overland flow formed a significant pond along the Beeches Road, and manhole surcharges in the east study area produced significant flooding area (Figure 2-(c)). Although the levees prevented the flooding from river channels, they also blocked the natural drainage paths and prevented the surface water flowing into channels such that the surcharge water accumulated in the regions next to levees. For the 1 in 100 year 15-minute rainfall event, the flood depth in the pond near Beeches Road reached 100 cm and the eastern region was almost completely submerged (Figure 2-(d)).



(a) 1 in 2 year (b) 1 in 10 year (c) 1 in 50 year (d) 1 in 100 year



(e) 1 in 2 year (f) 1 in 10 year (g) 1 in 50 year (h) 1 in 100 year

Figure 2. The maximum flood depth caused by pluvial events with various durations (top: 15-minutes; bottom: 60-minutes) and frequency of intensity

The flood scenarios were similar but more severe for rainfall events with 60-minutes duration. The discharges brought in by the two main pipes from upstream catchments were greater than 15-minutes events because the prolonged rainfall duration resulted in a larger surcharged volume in the study area (Figure 2-(e) to 2-(h)). Although the British Standard (BSI, 2008) suggests the design criteria for residential areas to be 1 in 2 year storm frequency, the results show that the large

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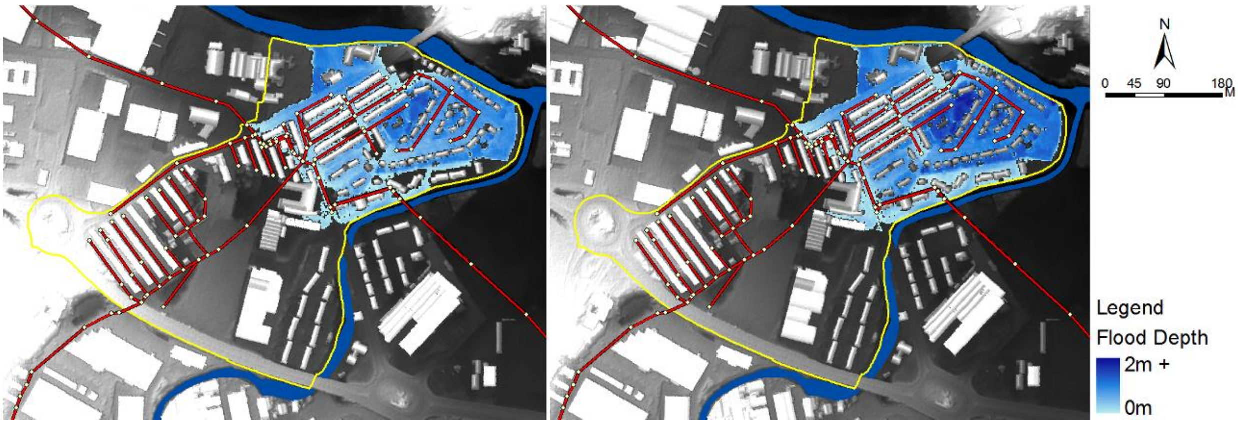
discharge from upstream in the main pipes that obstructed the downstream drainage in the east study area and incurred flooding. On the contrast, the manholes along Beeches Road were not surcharged during 1 in 10 year rainfall event because the intensity was less than the short duration event (15 min.) with same frequency. For the same reason, the flood depth in the pond along Beeches Road was also less for 1 in 50 and 1 in 100 year events than those 15-minutes ones with same frequency.

Fluvial flooding

An extreme condition with the peak water levels of 1 in 200 year return period in the river channel was applied to simulate the consequences of fluvial flooding. The 1 in 200 year river flood levels (for various cross sections) are about 23cm higher than the 1 in 100 year ones, which are greater than the crest elevation of levees. For reflecting the slow rising progress of flood levels in channels the duration of the event was set to 12 hours. The flood levels started at the crest elevations of levees and gradually increased to the peak during the first half of the event, then gradually decreased back to the crest elevation of levees in the second half. The height of current levees (1 in 100 year flood level + 10cm) was used as crest elevation for the overtopping scenario. The levees were instantaneously removed for the breaching scenario and the crest elevation reduced to the ground terrain elevation. The discharge was determined by the weir equation and introduced into overland flow model as lateral inflow/outflow. The same hydrograph pattern was also set as the downstream boundary condition of the drainage outlet. Although the flap valve protected the system from the backwater from the river, the high downstream water level also prevented the water in the sewer flowing into channel.

Both overtopping and breaching conditions were simulated independently and without rainfall inside the study area. The total overtopping and breaching peak discharge from the river were above 2.2 and 3.8 cms respectively, while as the design capacity of sewer system in the east study area was only 0.4 cms. Obviously, the sewer network could not deal with the runoff caused by such fluvial condition. Figure 3 shows the results of these two scenarios. The east study area was completely submerged and became a big pond during the overtopping and breaching fluvial events. The flooding extents in both results were similar because of the restriction of the terrain elevation. However, the breaching scenario generated greater flood depths because more flood volume could be discharged from the river channel. No manhole surcharged in the west study area near Beeches Road because there was no rainfall and the top elevations of manholes in the region were more than 87m, which were above 85.71m the highest peak in the river channel .



(a) Overtopping (b) Breaching

Figure 3. The maximum flood depth caused by overtopping and breaching flooding scenarios

Pluvial and fluvial flooding

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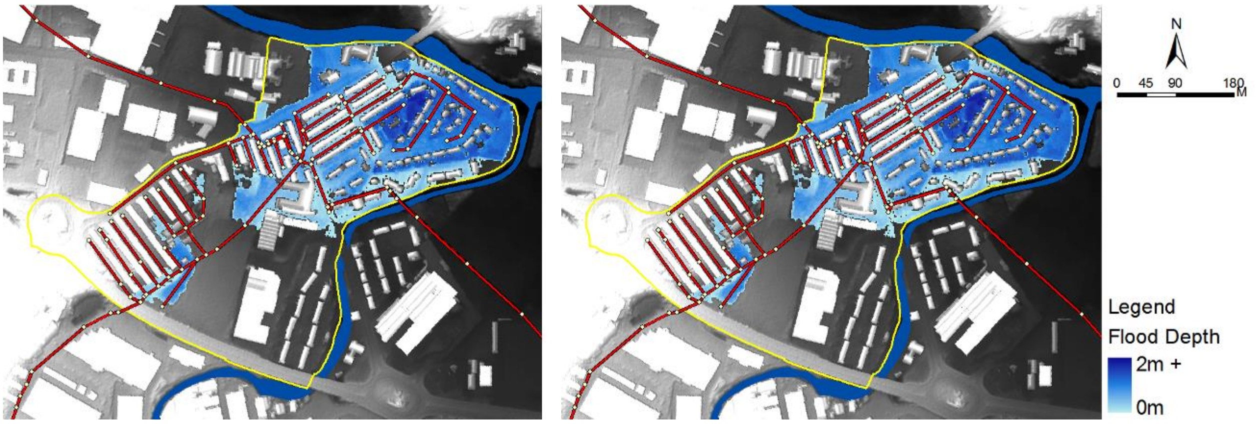
The pluvial and the fluvial flooding circumstances were combined for modelling to estimate the outcomes of the composite scenarios. The rainfall event matrix in Table 1 was combined with the overtopping and breaching scenarios. The heavy rainfall occurred at the beginning of events and the fluvial flooding lasted during whole 12 hours. Figures 4 shows the modelling results of a 60-minutes rainfall event with 1 in 100 year frequency associating with the overtopping and breaching scenarios with the peak river levels of 1 in 200 year return period. The joining of pluvial and fluvial conditions aggravated the flooding consequences. The flood extent and depths were bigger than those produced by a single type of flooding.

Table 2 compares the mean flood depth and the extent of flooded area caused by the selected pluvial, fluvial, and composite flooding scenarios. The isolated pluvial event (Figure 2-(h)) resulted in greater inundation area than the isolated fluvial events (Figure 3) because of the east study areas (the ponds near Beeches Road and in the south of River St.) were not influenced by the fluvial events. The wider spreading of surcharge water also reduced the averaged flood depth of the pluvial event.

Table 2. The mean flood depth and the flooded area of pluvial, fluvial and composite flooding scenarios.

Scenarios	Pluvial	Overtopping fluvial		Breaching fluvial	
	60 mins rain with 100y return period	Without rainfall	60 mins rain with 100y return period	Without rainfall	60 mins rain with 100y return period
Mean flood depth (m)	0.512	0.577	0.692	0.691	0.704
Flooded area (m^2)	56,572	43,660	62,542	47,492	62,896



(a) rainfall (100 year 60 minutes) combined with overtopping
(b) rainfall (100 year 60 minutes) combined with breaching

Figure 4. The maximum flood depth caused by composite pluvial and fluvial flooding scenarios

For the composite scenarios (Figure 4), the backwater from the downstream pipes affected the sewer drainage. The manhole surcharge in the west study area and the inundation areas were slightly larger than the one caused by the same isolated pluvial event (Figure 2–(h)). For the east study area, the flood depths and extents were exaggerated due to the combination of pluvial and fluvial flooding.

The main purpose of the paper is to provide an approach to analyse the flood causes for an area that is subject to both fluvial and pluvial flooding. The procedures can be applied to investigate different combinations of coastal, tidal, fluvial, pluvial and groundwater flooding. Some recent studies have discussed, mainly based on Monte-Carlo analyses, the joint probability of tidal and fluvial flooding, and failures of flood defences (Apel et al., 2006; Gouldby et al., 2008; Hall et al., 2003). The maximum water level and the peak discharge often dominate tidal and fluvial flooding because the fragilities of flood-defences are highly sensitive to these two variables. For the fluvial and pluvial events, not only the peak water level in river channels, but also the timing and the duration of local rainfall are critical to inundation. However, the combination of the two events is complex and discussion regarding the joint probability can be found in the literature (Dawson et al., 2008). We recognise that the fluvial flooding, caused by heavy rainfall in upstream catchments, and the pluvial flooding resulted by intense precipitation in local area, are unlikely to be independent in most cases. De Lima and Singh (de Lima and Singh, 2002) found the patterns of moving storms, including shape, duration, speed and direction, to affect the peak discharge and hydrograph shapes significantly. We believe the joint probability issue is worth for in depth research regarding rainfall characteristics, which include intensity-duration-frequency (IDF), spatial-temporal distributions, and rainfall-runoff relationships, for further applications to flood risk assessment.

The modelling results were integrated into a GIS database for further analysis. The individual and composite flooding extents were overlapped and compared to each other scenarios. Figure 5 shows the flood extents of composite flooding, which were categorised by main driver of flooding. The majority in the east study area suffers from both pluvial and fluvial events. Either scenario would introduce flooding problem in the region. However, for the areas next to levees, the pluvial flooding could be eased if portable pumps were applied. Only a minor part in the region is subject to fluvial flooding because of the ground elevations are higher pluvial flooding does not affect the area. The inundation in the west study area was mainly generated by surcharge from the sewer system such that the pluvial events dominate the flooding problem in the region. There are also few areas that were flooded only during composite events.

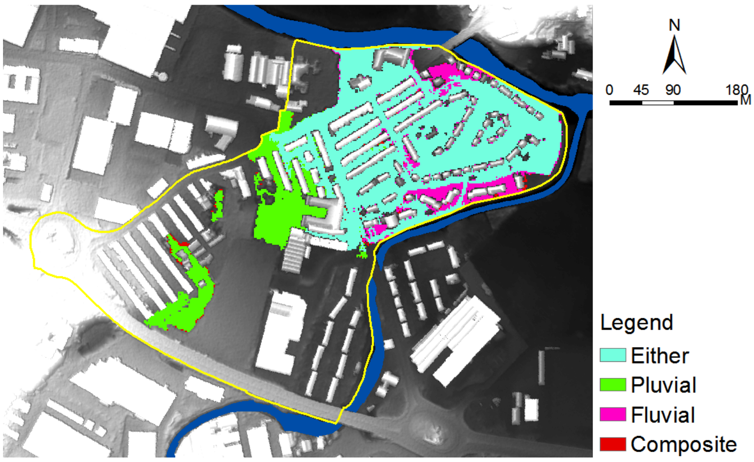


Figure 5. The categorised main driver of flooding.

CONCLUSIONS

The numerical modelling study combined a matrix of pluvial rainfall events with fluvial flooding scenarios. The results were analysed to identify the dominating driver of flooding in different parts of the case study, providing better understanding to flood risk management. Further studies regarding the details of flood propagation during heavy rainfall events could implement the knowledge of interactions of pluvial and fluvial floods. Appropriate strategies can accordingly be developed to cope with specific flood conditions to mitigate flood-hazard more successfully.

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