Assessing Urban Flood Risk with Probabilistic Approaches

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Submitted in accordance with the requirements for the degree of Doctor of Philosophy

The University of Leeds
Institute of Resilient Infrastructure

School of Civil Engineering

November 2017

Acknowledgements

I would like to express my gratitude to my supervisors; Professor Nigel Wright, Dr. P. Andrew Sleigh and Dr. Sangaralingam Ahilan for their supervision, guidance, and support on my PhD project.

I would like to thank to Republic of Turkey Ministry of National Education for funding my PhD.

I would like to thank to Simon Jepps and John Jepps, and TUFLOW support group.

I would like to thank to the friends and colleagues at the School of Civil Engineering Yuhan Zhao, Mark Brotherton, Claudia, Thomas, Andrea, Sura Faleh, Carolina and Water@Leeds group.

I sincerely would like to thank to my mother Oya Sertyesilisik.

Abstract

Flooding is a serious natural disaster in urban areas. Moreover, the consequences of land use change and rainfall can affect the flood process in urbanised catchments. Fluvial flooding can be seen at downstream locations due to the high and fast discharge from sub-catchments. In addition, pluvial flooding can be seen at settlements are situated on the floodplains by river channel at downstream locations, due to the impermeable surfaces and insufficient drainage capacity. Therefore, the combined pluvial and fluvial flooding can be observed on the floodplains of urban stream basins. Although, flood risk can be severe for these places, research on combined fluvial and pluvial flooding is very rare.

One of these places is Wortley Beck catchment, Leeds, UK. To observe the interaction between fluvial and pluvial flooding, the floods were modelled for different land-use scenarios and rainfall events for an urbanised and ungauged catchment. The inflow hydrographs and rainfall hyetograph were designed by using the ReFH rainfall-runoff method. 1D and 2D hydrodynamic models were used to simulate fluvial and pluvial flooding.

The outcomes were peak flow values and probabilistic inundation maps with maximum water depth values. The peak flow values were used to investigate the relationship of return period between rainfall and flow by using the FEH statistical model. The effects of the land use change and rainfall on the flood risk were observed from the maps. In addition, the flood extent of combined pluvial and fluvial flooding was observed from these maps. Water depth values in the inundation area by combined flooding were computed. Hence, fluvial flooding in combination with pluvial flooding was observed to have a higher flood risk in the urban stream basins. These outcomes can be used to manage flood risk due to land use change in the future for ungauged catchments by National and Local Governments.

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Chapter 1 Introduction

Changes in watershed hydrology may affect the catchment water balance thus causing, as a result, adverse hydrological events such as a flooding and droughts (Weng, 2001). Flood events can be observed when a normally dry land is inundated. Magnitude, frequency, and duration are fundamental parameters for consideration of the effect of a flood event. The parameters that govern a flood event are varied, uncertain, and very difficult to estimate. For instance, a flood event can re-occur at irregular intervals and with varying magnitude and duration. It means that to predict with accuracy the timing and magnitude of any particular flood event in a given location is a significant challenge. Furthermore, the consequences of flood events may depend heavily on floodwater depth, return period, the location of the inundated area and the length of the event itself. These add that the designing of appropriate (i.e. offering sufficient protection for acceptable cost) flood defences is difficult (Jha et al., 2012). Moreover, there are several reasons why flooding occurs, for example, flooding may be the result of natural circumstances, human actions or, very often, a combination of both (Calder and Aylward, 2006). In addition, within a particular catchment, one or more of several types of flooding processes and their combinations can often be observed namely: fluvial flooding, coastal flooding, pluvial flooding, and groundwater flooding (Thorne, 2014). Any or all of these flood events can have negative effects on residences, sewerage systems, agriculture and the economy and these may be anywhere on the planet (Marsh et al., 2016). Consequently, to manage the flood events, flood frequency and consequences are the primary parameters to examine. Both the frequency and the consequences of flooding are affected by future changes in land use and climate (Ashley et al., 2005).

Flooding is possible in anywhere in the world, where it rains, and it is a significant risk worldwide (Guha-Sapir et al., 2016). Flooding is often described as being the most dangerous natural disaster (MunichRe, 2015). Guha-Sapir et al. (2014) reported that nearly 10000 people were killed from flooding in 2013 in the world. Furthermore, the most frequent natural disaster has been flooding specifically, between in 1994 and 2013 years (UNISDR, 2015). Flooding is the most frequent disasters in Asia also (Budiyono et al., 2015). In addition, the flooding happened in 2014/2015, 2013/2014, 2009, 2007, 2006, 2000/2001, 1998, 1995, 1990, 1986, 1982, 1974, and 1968 years at the regional scale in the UK (Marsh et al., 2016).

In all of these cases, there is a significant impact on the economy in all over the world. Floods are one of the biggest reasons for the economic losses from the natural disasters (UNISDR, 2009). Annual economic losses from natural disasters decreased between 2003 and 2012 years in all areas, except flooding. Estimates of the cost of flood damage have been put at US$ 53.2 billion in 2013 in the world (Guha-Sapir et al., 2014). Similarly, the cost of property damage is high. More than 5 million properties can be at flood risk in the UK (Thorne, 2014). It is clear that expense has increased sharply due to the effects of flood damage. The budget can be expected to rise because annual damage of flooding could increase in the future (CCRA, 2012). Besides the economic cost of flooding, consequences of flooding can also cause of disruption of daily life, industrial and agricultural production (Pitt, 2008). During and after flooding, life routine can be disrupted in both urban and rural areas. For instance, flooding can cause disruptions in transportation or water supply system (Rafiq et al., 2016), e.g. the water supply and electrical system were not functional for a while following the July 2007 floods in the UK (Pitt, 2008). Similarly, some residences were left without power because of the flood event on the Christmas 2013 in the UK (Thorne, 2014). A further potentially more widespread effect could occur in the form of diseases and discomfort trauma (Ahern et al., 2005). For instance, Malaria and leptospirosis diseases can spread because of contamination after flooding (Hammond et al., 2013). Lastly, cultural heritage can also be damaged by the flooding (Nedvedová and Pergl, 2013).

The rainfall-runoff process in urban areas is that during or immediately after the precipitation event, rainfall can enter the subsurface by infiltration through permeable surfaces in parks and gardens, storm runoff can be conveyed by sewer system and discharged into river channel**.** The rainfall-runoff process in urbanised catchment may depend heavily on the magnitude of a rainfall event, the capacity, quantity of the permeable surfaces, and the effectiveness of the sewer system in the city (Dawson et al., 2008; Rafiq et al., 2016).

When climate change and urbanisation are incorporated into this process, the consequences of flooding can be much serious in the future. The magnitude of the rainfall event can be a major contributory factor of flood risk in the UK (Marsh et al., 2016) while climate change is expected to increase the rainfall intensity and frequency and thus the magnitude (Waters et al., 2003). Therefore, climate change can affect the magnitude of flood risk. For instance, 1 % AEP river flood can increase 20% from 2025 year to 2115 year in England due to the climate change (DCLG, 2010).

In addition, urbanisation is constantly expanding in terms of space and population density throughout the world. Population is expected to rise to 6.3 billion in 2050 in urban areas (Nations, 2014), due to the economic growth, employment opportunities, better living standards, and education in cities (Turok and McGranahan, 2013). Therefore, land use in cities is changing from green fields and permeable areas to the impervious areas by building residential areas, roads, highways, roofs, pavements, car parks, industrial places and asphalt surfaces (Cheng and Wang, 2002; Evans et al., 2008; Abdullah, 2012) by Governments, city councils and businessmen. The increased ratio of impervious surfaces on previously rural land, (due to the urbanisation process of a watershed), increase the volume of water runoff, and flood peak, or reduce the infiltration, and the time of catchment response (Weng, 2001; Cheng and Wang, 2002; Abdullah, 2012). In fact, it is common to see ephemeral ponds on the low-level surface during high rainfall.

This urban surface water becomes a flood, when it is too deep, extensive or it stays too long i.e. does not drain or is not managed (Shi et al., 2007; Wheater and Evans, 2009; Du et al., 2015).

Capacity and performance of the infrastructure systems rarely can manage heavy runoff in streets effectively. The performance of a sewer system can have a significant impact on the flood management in the cities. When the surface runoff cannot be managed by the sewer system due to being overwhelmed with water, the runoff process can become a flooding situation (Dawson et al., 2008). For example, debris, rubbish inside of the pipe system can affect the capacity of the sewer system. Furthermore, some infrastructure systems are designed as combined storm water and sewerage system. These can be resulting in that the infrastructure system struggle to manage and to collect surface runoff in the streets along with the sewage, so that pluvial flooding can occur as local flooding or backup events in urban areas (WMO and GWP, 2008; Abdullah, 2012; Rafiq et al., 2016). According to OFWAT (2002), in the UK, 16,000 settlements have been identified as at risk of being affected by the 10-year return period of a sewer flooding, which means that pluvial flood is a high risk for these places. Whatever the capacity issue is with existing infrastructure systems, maintenance and upgrading of the systems to increase their performance are never cheap or easy. Impermeable surfaces, the lack of sewer system and growth of population in the flood-prone areas have the significant influence on flood incidents in urban watershed. These have resulted in flooding becoming a serious problem in cities all over the world (Jha et al., 2012). Some of the cities that have been particularly affected are Bangkok, Dhaka, Jakarta, and Kuala Lumpur (Abdullah, 2012). In the cities, the management of the factors of urban flood risk is becoming an emergency mission. Climate change and urbanisation can increase the risk to assets and population that are the exposure to floods in urban areas. Therefore, climate change and urbanisation can be considered the primary factors of concern for the future for predicting flood events in urban areas (Merz et al., 2010; Yin et al., 2015).

Besides the climate change and land use change factors, the combination of flood events can be added into the strategies of flood risk management to be addressed in urban areas (Cheng and Wang, 2002; Re, 2005; Dawson et al., 2008; Evans et al., 2008; WMO and GWP, 2008; Ten Veldhuis, 2010; Singh and Singh, 2011).

Various flood events such as coastal flooding, fluvial flooding, pluvial flooding, and their combinations can be observed in urban areas due to the location (Ten Veldhuis, 2010). Coastal flooding can happen, where the cities are settled by a coastline, at high sea water levels. Fluvial flooding can happen, where the cities are settled by a tributary, by overflowing of riverbanks (Burton et al., 2010). Furthermore, the processes of these flood events can have a relationship. Therefore, a combined flood event can incur from the combination of these various floods in urban areas. More than one simultaneous flood events can be observed such as, overwhelmed urban stream channel and coastal with high sea levels, or tidal and surface runoff (Ten Veldhuis, 2010; Lian et al., 2013; Thorne, 2014; House of Commons, 2015). Flood events such as those in the UK in winter 2013/14 were results of a variety of combinations of tidal, rainfall, river, and groundwater source (Thorne, 2014). Asian mega-cities are prone to the combination of flood events due to their extraordinary urban growth by river channels and their monsoonal rainfall events (Chan et al., 2012), these resulting in both pluvial flooding and fluvial flooding, and are being observed either consecutively or coincidentally in these locations. Similarly, in tropical regions in smaller towns and cities the annual monsoon, local intensive precipitation events are observed (and predictable) and often result in both fluvial and pluvial flooding occurring at the same time (Apel et al., 2015). Chen et al. (2010) and Apel et al. (2015) pointed out that the reason of a fluvial flooding is heavy rainfall in upstream locations while the reason for pluvial flooding is intense precipitation in the local area.

The process of the combined pluvial and fluvial flooding in urban areas can be explained as that. Historically, people have settled near the rivers. Settlements have been built on the floodplains thus impermeable surfaces have rapidly grown up along the rivers (Evans et al., 2008).

Urbanisation on the floodplains such as farmland, forested land can reduce the land’s ability to retain rainfall thus the generation of surface runoff and of discharge from the sub-catchments may increase (WMO and GWP, 2008; Du et al., 2015).

These lowland locations also have a potential to have riverine flooding (WMO and GWP, 2008; Hammond et al., 2015). These locations are usually low cost, so become subject to being impacted by the spatial distribution of population. This situation is likely to encourage more settlements on the floodplains (WMO and GWP, 2008). Therefore, the urban drainage system cannot manage runoff after an intense rainfall event and pluvial flood events can occur in these locations. Consequently, intensive precipitation on saturated soil and impervious surfaces, an excessive flow load within a sewer/storm water system, also an overwhelmed river channel with inadequate flood defence structures on the floodplains in urban stream basins can cause combined pluvial and fluvial flooding.

In general, the impact of the fluvial and pluvial flood events are analysed separately. Studies considering the combined effects of fluvial and pluvial flooding in detail are very few (Apel et al., 2015; Breinl et al., 2015). Furthermore, Chen et al. (2010) and Ashley et al. (2005) implied that the effects of the combination of fluvial and pluvial flood events can be severe than their individual potential effects. Burton et al. (2010) added that if simultaneous flood events are analysed separately, the hazard could be underestimated.

Briefly, as land use change, population and climate change parameters are considered for urbanised catchments, flood frequency and magnitude of flood damage can be expected at significant level in the future (Ten Veldhuis, 2010). All these aspects make flood resilience approaches to be insufficient in the future. Therefore, the urban flood risk might have assessment priority alongside other natural disasters (Winsemius et al., 2013). The primary challenges can be to predict the process of the urban flood event, to construct resilient infrastructure, and to update these approaches (Hammond et al., 2015).

Probabilistic approaches can be applied to adapt flood inundation analysis with future growth taken into account in the urbanised catchments (Yanyan et al., nd.; Thompson and Frazier, 2014).

These strategies are not likely to be low cost and can require long-term adaptation plans, and various vulnerability assessments (Budiyono et al., 2015) by local and national planning boards. To apply flood defence strategies with the long-term adaptation plans estimation of the future flood risk is always required. Adaptation scenarios can be created to define these risk factors by setting up the hydrology models, hydraulic models, and flood damage assessment models (Yanyan et al., nd.).

In conclusion, changes in water balance in a watershed can cause flood events. Magnitude, frequency, and duration of flood events have many uncertainties. These facts make difficult the estimation of flooding. Flooding is one of the most dangerous natural disasters. Urban areas are most prone to flooding. These locations have many more frequent flood events, severe damage, destruction of the properties and the human life than rural areas. In addition, the effects of the land use change and climate change on the flood processes can have multiple and changing aspects. Due to urbanisation and climate change, the ratio of saturated surfaces decreases and with high rainfall magnitude, surface runoff cannot be managed by the sewer system in the cities. These can result in various flood events and their combinations in urban areas. Old-style and single-line wall flood defences of a single flood event can be recognised as ineffective for these events. Moreover, it is clear that the definition and understanding of the interdependencies of the flood processes are essential to developing the flood defence systems. In addition, the analysis of the frequency, magnitude, and interaction of any flooding are required for the advanced and predictive assessment of the urban flood risk. As a consideration of this, Sustainable Urban Drainage Systems (SUDS) as a toolbox of solutions might be useful to attenuate runoff.

All of the above contribute to the easily drawn conclusion that urban flood risk assessment deserves priority amongst the other natural disasters. National and local governments have an imperative to achieve the balance between urbanisation and vulnerability to flooding due to the economic growth and population in cities. To manage the land use change and to adapt to the climate change are essential approaches to analyse and mitigate the consequences of flood risk. It is important to note that the influence of climate change and urbanisation on the relationship between direct runoff generation and flood risk are not straightforward. Therefore, significant research is needed and ongoing in this area. To update and modify strategies of the flood risk management for the future and the variety of flood events will always be necessary.

1.1 Research framework

1.1.1 Aim

The aim of this research is to assess the urban flood risk to enrich the mitigation approaches of the adverse flood consequences in urban areas of local government agencies.

1.1.2 Objectives

To reach the aim the below objectives have been set,

1. To analyse the impact of land use changes on flood risk in urban basins.

2. To analyse the impact of rainfall events on flood risk in urban basins.

3. To develop a method to assess the interactions between the fluvial and pluvial flood events in urban basins.

All research was undertaken at the representative urban catchment, Wortley Beck catchment, Leeds, UK.

1.1.3 Research methodology

This section gives a brief explanation of the methodology of this research.

The case study was developed for Wortley Beck catchment. Wortley Beck catchment has three sub-catchments. These are Farnley, Farnley Wood, and New Farnley basins. Wortley Beck catchment is an ungauged and urbanised catchment. The flood risk of the Wortley Beck catchment was analysed by simulating three flood processes. These were fluvial flooding, single event, and pluvial flooding.

The probabilistic flood events were simulated by using hydrodynamic models. One- dimensional (1D) hydraulic model was used to simulate river system of the Lower Wortley Beck. Flood Modeller Suite (v 3.7.0) software was used for this simulation. Flood Modeller Suite software was developed by CH2MHILL and was benchmarked by the Environment Agency. Flood-prone areas of the Wortley Beck catchment were simulated by using a two-dimensional (2D) hydrodynamic model. Two-dimensional Unsteady FLOW (TUFLOW, 2013-12-AD-w64) software was used for this simulation. TUFLOW was developed by BMT.

The urban flood risk can be assessed based on the results of the simulations. The outcomes from this research can be used to improve urban flood resilience tools in Wortley Beck catchment. In this study, the sewer system is neglected neither pluvial nor fluvial, due to its limited capacity in the hydraulic flood simulations.

A.) Modelling of fluvial flooding

To assess the impact of the discharge at the outfall of the sub-catchment on the downstream fluvial flood risk, fluvial flood event simulation was undertaken.

The following methodology steps were used to simulate the probabilistic fluvial flood events at the Lower Wortley Beck, Leeds, UK,

1. The inflows from Farnley Beck and Farnley Wood Beck basins were estimated for different return periods, by using the Revitalised Flood Hydrograph (ReFH) model.

2. A coupled 1D-2D hydrodynamic model was set up.

B.) Modelling of single event simulation

To assess the impact of the peak flow at the outfall of a sub-catchment on the downstream fluvial flood risk, single event simulation was undertaken. The maximum discharge was used to display the surface runoff at the upstream basin. The peak flow at the outfall of a sub-catchment was modelled as a lateral flow in the river system. New Farnley sub-catchment was assessed and utilised for this approach.

The following methodology steps were used to simulate the probabilistic single event at the Lower Wortley Beck, Leeds, UK,

1. The Rational model was used to calculate peak flows for various return periods.

2- A coupled 1D-2D hydrodynamic model was set up. In addition to the inflows, lateral flow was integrated within the fluvial system of the Lower Wortley Beck.

C.) Modelling of pluvial flooding

To assess the surface flood risk in the Wortley Beck catchment, a direct rainfall-runoff model was set up.

The following methodology steps were used to simulate the probabilistic pluvial flood events at the Wortley Beck catchment, Leeds, UK,

1. A net event hyetograph was estimated by using the Revitalised FSR/FEH loss model. Rainfall events were produced by using the Flood Modeller Suite ReFH boundary framework.

2. Rainfall-runoff process was simulated by using a 2D hydrodynamic model.

3. Surface runoff was modelled for permeable and impermeable surfaces.

4. Peak flows were computed from various rainfall events.

D.) Calibration

Calibration process was carried out by using measured rainfall and water level data. Measured rainfall data set was taken from Headingley, Knostrop, and Heckmondwike rain gauges stations. The water level data was taken from Pudsey stage gauge station. The data sets were supplied by the UK Environment Agency and Met office in 2016 for this research.

E.) Probabilistic flood inundation maps

It was essential to produce flood inundation maps for a range of annual exceedance probability (AEP) to identify vulnerability of regions within this urban area, which could then be translated to reach generalizable conclusions on the effect of other urban areas. Probabilistic flood inundation maps with water depth were produced by using the outcomes of the hydrological and hydraulic models simulations. These maps were used to identify the flood vulnerable areas in the research areas. Hydrodynamic model was linked geographic information system (GIS) tool to produce these maps by using LiDAR data and the master map of the catchment.

Catchment surface was investigated by using the LiDAR data, and Master Map. The data sets and surface roughness parameters were supplied by the UK Environment Agency and Leeds City Council for this research. Background of the probabilistic flood inundation map was created by using the ordnance survey 1:25 000-scale colour raster in this research.

1.1.4 Research steps

The below research steps were taking to reach the objectives.

Fluvial and pluvial flood processes in urbanised catchments were simulated in this research. The flood events were designed by using the following parameters: different ranges of land use scenario, rainfall duration, and annual exceedance probability.

1. The impact of land use change (urban developments, SUDS) on the flood risk were analysed in this research.

2. The impact of rainfall events on the flood risk were analysed in this research.

3. The interaction between fluvial and pluvial flood drivers on the floodplains of urban stream basins was assessed in this research.

Step 1. Analysis of the impact of the land use change on flood risk in urban basins

The impact of the land use change (urban developments, SUDS) on flood risk was analysed by adjusting the ratio of impermeable surfaces. Thus, the effects of the impermeable surfaces on surface runoff and on outflow discharge of the sub-basin could be examined. This also means that the impacts of the land use on the downstream flood risk could be observed.

The ratio of the impermeable surface was adjusted by using URBEXT parameter. The URBEXT is a catchment descriptor parameter, which refers to the extent of urban and suburban land cover for a specific year.

The URBEXT was used to calculate different urban growth ratios of various years in this research.

Step 2. Analysis of the impact of rainfall events on flood risk in urban basins

Climate change is expected to affect rainfall events. The effects of rainfall events on pluvial flooding and downstream fluvial flooding were investigated in this research. The rainfall event analysis was performed by using various rainfall durations and return periods in this research.

The Wortley Beck catchment is an ungauged catchment. Therefore, the flood events were designed from the rainfall-based hydrological model. Catchment response time is used to estimate rainfall duration in this research. The link between rainfall event and flood risk can be determined by using assessments of the catchment response time.

Step 3. Assessment of the interactions between the fluvial and pluvial flood events in urban basins

To assess the interaction between the fluvial and pluvial flooding in urban basins, various fluvial and pluvial flood events were simulated. In addition, the combined fluvial and pluvial flooding on the floodplains of urban stream basin was analysed.

Firstly, the fluvial flood events at the Lower Wortley Beck area were designed. Secondly, the single event simulations were modelled to understand the impact of the lateral flow on the downstream fluvial flood risk. Thirdly, the pluvial flooding was designed on the Wortley Beck catchment. Lastly, the combined fluvial and pluvial flood events on the floodplains of the Lower Wortley Beck were modelled.

The interaction between fluvial and pluvial flooding in the urban areas was investigated by using the below approaches.

1. Assess the fluvial flood model and single event simulations,

2. Assess independent fluvial flood events and pluvial flood events,

3. Determine the relationship between the return period of the rainfall and the return period of the flow,

4. Assess the combinations of the pluvial and fluvial flood events on the floodplains of the Lower Wortley Beck.

The interaction between the fluvial and pluvial flood events on the floodplains was determined by using flood frequency, flood extent, flow values, and water depth parameters. The probabilistic flood inundation maps and water level results were used to present the independent and dependent relationship between fluvial and pluvial flooding.

3.1) Assessment of the fluvial flood model and single event simulations

The probabilistic fluvial flood events were simulated to observe the Lower Wortley Beck fluvial flood extent. Inflow event hydrographs of the Lower Wortley Beck were estimated for Farnley Beck and Farnley Wood Beck sub-catchments of the Wortley Beck catchment. Probabilistic single flood events were simulated to observe the impact of the peak discharge at the outlet of New Farnley Beck basin on the Lower Wortley Beck fluvial flood extent. In addition to the inflow hydrographs, the lateral flow was integrated within the simulations. These simulations were designed for various return periods and urbanisation scenarios. The advantage of this method is to analyse the interaction between surface runoff in the upper catchment and river flow at the downstream.

Limitation of this method can be that lateral flow was applied as constant during the simulation. However, the lateral flow and inflow of the fluvial flood event could have different time durations and peak time.

3.2) Assessment of independent fluvial flood events and pluvial flood events,

1. Fluvial flooding and pluvial flooding were modelled by using various return periods.

2. The probabilistic flood inundation maps with water depth scale were produced by using the results of the simulations.

3. The common flood-prone areas were observed for a specific return period.

The advantage of this method is to design various pluvial and fluvial flood events in Wortley Beck catchment. A limitation of this method is that the interaction between pluvial and fluvial flood risk cannot be captured in detail.

3.3) Determination of the relationship between the return period of rainfall events and the return period of flows

The Regional (Pooled) approach of the statistical flood estimation method was applied to determine the return period of flows from the specified return period of rainfall events.

A rainfall-runoff model was set up to analyse flood frequency for an ungauged catchment, by using 2D TUFLOW hydrodynamic model. The advantage of the usage of 2D TUFLOW for a rainfall-runoff model is that it is capable of computing the flow over the whole period at selected locations in the research area for each rainfall events. This application was very suitable to compute peak flow in the ungauged catchment.

3.4) Assessment of the combinations of the pluvial and fluvial flood events on floodplain

The interdependency of pluvial and fluvial flooding has been discussed for the Lower Wortley Beck area in this research. The combined fluvial and pluvial flooding was simulated by using the 2D direct rainfall model link with the river channel in Lower Wortley Beck area. Inflow hydrographs of the sub-catchments of Wortley Beck and net rainfall hyetograph of the Lower Wortley Beck area were integrated within the simulations. Thus, the flood extent with water depth of the combined fluvial and pluvial flooding on the floodplains of the Lower Wortley Beck can be simulated and observed.

Probabilistic flood inundation maps with water depth scales were used to display the flood-prone locations from combined fluvial and pluvial flood events on the floodplains of the Lower Wortley Beck area.

According to this approach, various combined fluvial and pluvial flood events can be simulated. In addition, the consequences of the combined flood events can be observed.

1.2 Wortley Beck catchment

The research area is Wortley Beck catchment. This catchment is located in the south-west of Leeds, UK. The basin is approximately 63 km^2 and drains into the River Aire. The catchment consists in Farnley Beck, New Farnley, and Farnley Wood Beck sub-catchments (Figure 1.1).This catchment is ungauged and urbanised.

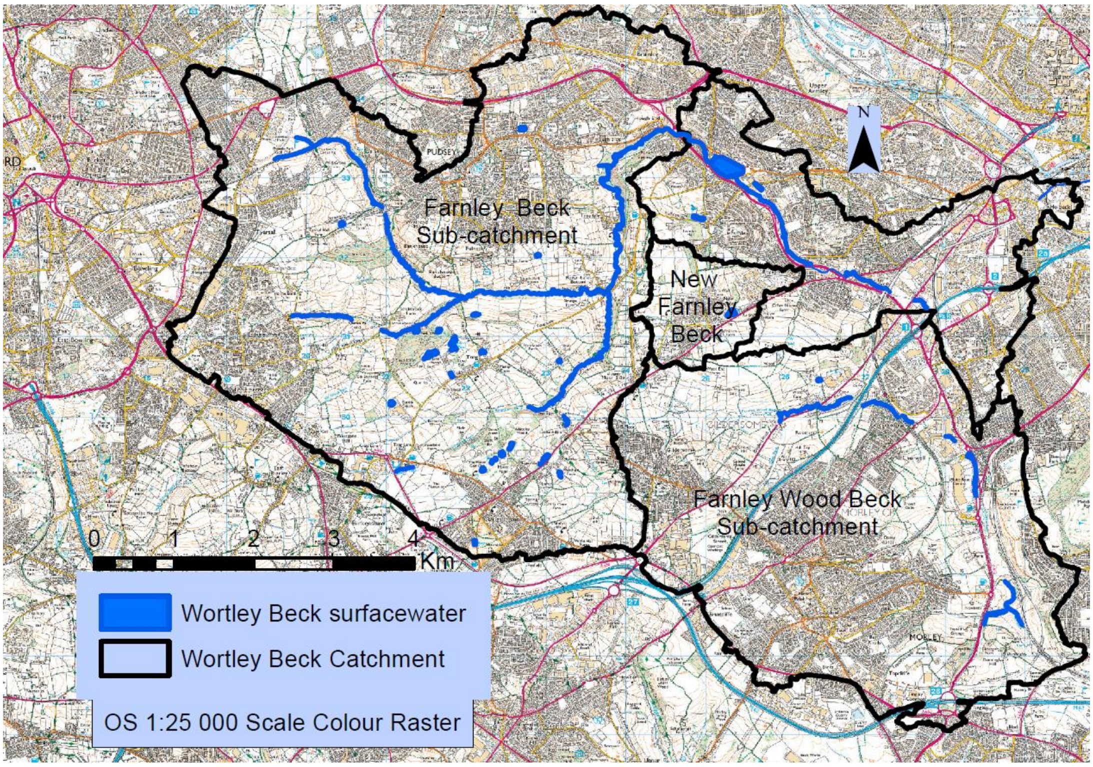

Figure 1.1 Wortley Beck catchment

1.2.1 Flood risk in Wortley Beck catchment

Flood alert areas of the Wortley Beck catchment can be found in Figure 1.2. This area has been flooded since 1886 (Atkins, 2004). Historically, Wortley Beck catchment was flooded in 1946, 2005, 2007 (Hope, 2011). Moreover, Atkins (2004) informed that flooding occurred at the Farnley Wood Beck and Farnley Beck basins in 1946, on September 1993, December 2000, and August 2002.

In addition, in the Christmas period, in 2015/2016, approximately 1,000 homes were flooded in Leeds as the Aire River overtopped its banks (Marsh et al., 2016).

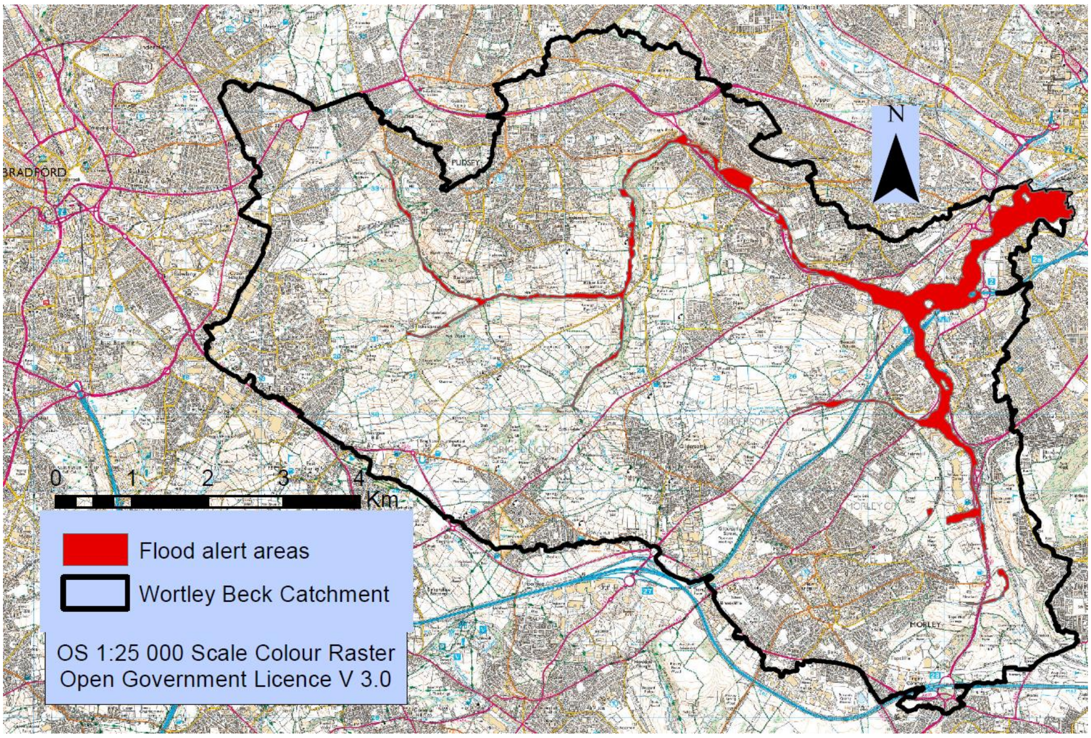

Figure 1.2 Flood alert areas of the Wortley Beck catchment

Flood risk assessment of the Lower Wortley area was the focus of this research. This location was selected because there are important settlements, industrial areas, state buildings, and transportation links (Ring Road, M621 Road) in the flood alert areas. In addition, there are new built-up areas along the route of the Lower Wortley River. Lastly, there are two critical important structures in this area. These are Farnley Flood Storage Reservoir and culvert.

A.) Flood risk before Farnley Flood Storage Reservoir

Figure 1.3 is a historic flood map and shows the historical flooding location upstream the Farnley flood storage reservoir. The historic flood data was provided by the Environment Agency. The area was labelled as ‘1’ is at the junction of Wood Road and Pudsey Road. The area was labelled, as ‘2’ shows above the Farnley reservoir (Figure 1.3). The reason for the flooding of this location could be reservoir has overtopped.

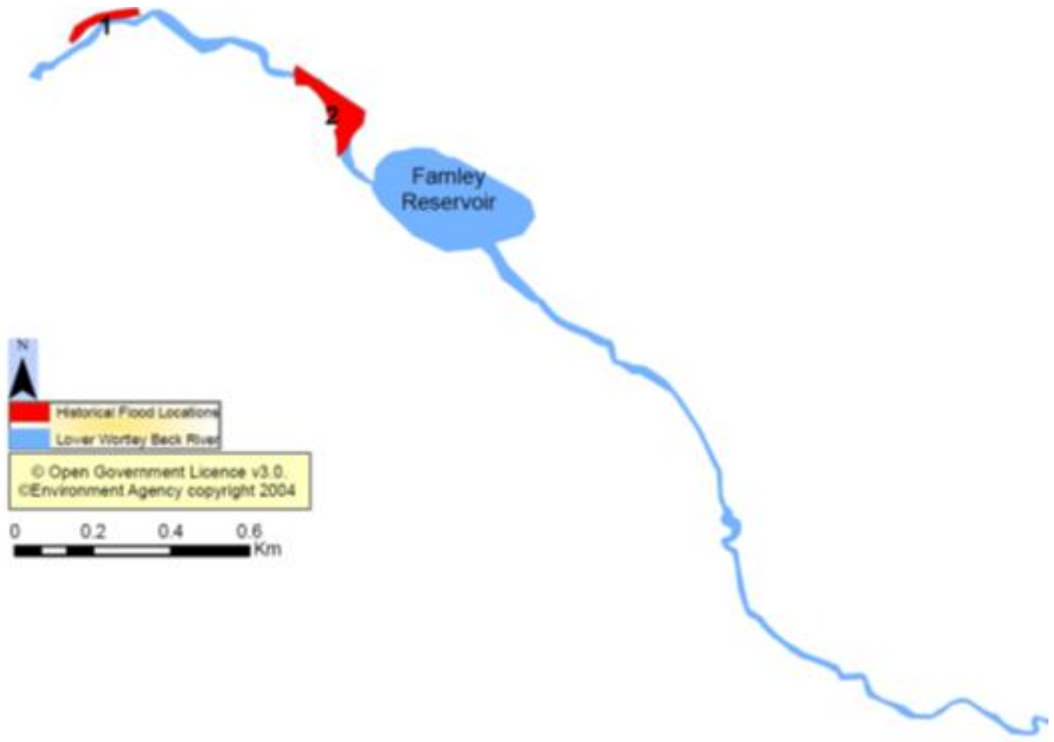

Figure 1.3 The historic flood map

1.2.2 Farnley flood storage reservoir

Farnley flood storage reservoir was built to manage the flood risk in the Lower Wortley Beck area by attenuating flows for a 15-year return period. However, this reservoir is not efficient in its present state because it filled with silt, rubbish, and sediments (Figure 1.4 and 1.5). In order to use it with original capacity, it should regularly be cleaned and maintained, which is very expensive and difficult.

Figure 1.4 Farnley flood storage reservoir picture 1

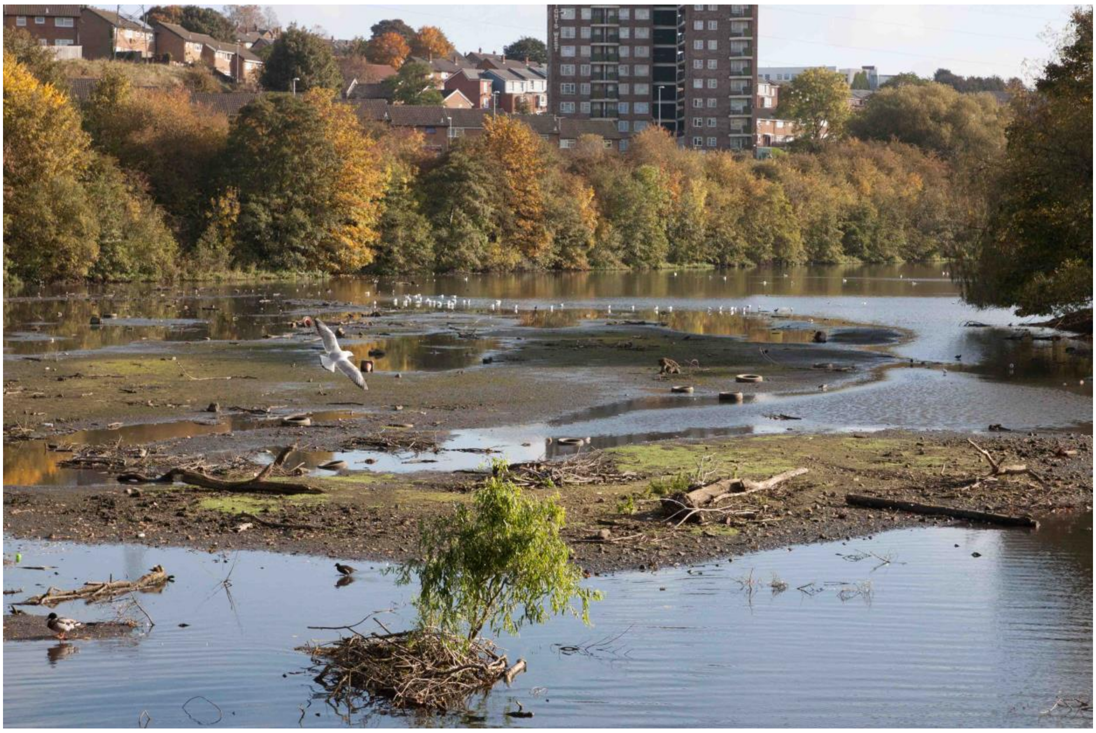

Figure 1.5 Farnley flood storage reservoir picture 2

1.2.3 Culvert and backwater effect

A culvert is located at the junction of the Ring Road and M621, in the Lower Wortley Beck area. The capacity of the culvert is generally not sufficient for the flow. Culvert can be blocked so the backwater effect can be observed.

1.2.4 Flood risk assessment in the Wortley Beck catchment

The first flood risk assessment of Wortley Beck catchment report was produced by Atkins, in 2004. This report analysed the 18.0 km length area by using unsteady one-dimensional hydrodynamic model. Atkins- Transport Solutions Warrington - Survey Department completed a topographic survey in October 2003 for this report. Outcomes of this survey were used to determine the hydraulic characteristics of the channels such as roughness values, the physical properties of cross section and hydraulic structures. The hydraulic model was version 2.2 of the Flood Modeller Suite (ISIS) one-dimensional model. Farnley Flood Storage Reservoir and culvert were built to manage the flood risk. However, the reservoir and culvert could have limited capacity for the flow. There could be backwater risk in the area. Potential flood risk was found at the Ring Road in Lower Wortley. The model could not be calibrated. Some recommendations of this study were to have a measured data to calibrate the model, to update the topographic survey data, to maintain regularly the hydraulic structures and to update the URBEXT values to analyse the impact of urban growth on the flood risk (Atkins, 2004).

Another report was prepared by the Thomas Mackay Ltd as required by PPS25. The flood level and extent were examined in this report because flood risk was severe at the Farnley Beck basin. Hydrological data, topographical data, roughness values of the cross sections, and 1D model schematisation were the same as Atkins (2004)`s research. The 1m resolution LiDAR data of Environment Agency was used in this research. The research area was visited on 22 July 2010 for this research. The Flood Modeller Suite (1D ISIS version 3.4) model was linked to the TUFLOW 2D model to simulation. Ordnance Survey Master Map with scale 1:10000 was used to model 2D domain of the research area. The 2D domain 6.7 km^2 area was modelled with a cell size of 5 metre.

The downstream of the model was at the River Aire. Flood extents maps were produced for a fixed time step of 1 second in the 1D domain and 2 second in the TUFLOW 2D domain. Lastly, the model could not be calibrated (Jepps, 2011). This report recommended that hydrological assessment should be updated (Jepps, 2011).

Consequently, the reports recommended a further research for the Wortley Beck catchment to update the fluvial flood risk assessment. The updates could contain in calibration the model, in a new survey data, or in a high resolution updated topographical data.

1.2.5 The suitability of Wortley Beck catchment with the research purpose

Wortley Beck catchment is an urban stream basin. There are some settlements and population along the route of the river. In addition, this location has built-up areas. Moreover, the ratio of impermeable surfaces has increased on the floodplains. Therefore, the catchment has several levels of both fluvial and pluvial flood risk. In addition, the combination of fluvial and pluvial flood event can be observed more often than the present in the future. The consequences of flood events will be much serious. Lastly, updated information is necessary to manage the future flood risk for Wortley Beck catchment.

Chapter 2 Literature review

2.1 Existing combination methods of fluvial and pluvial flooding

In this section, the evaluation of methodologies for assessing combined fluvial and pluvial flooding is presented.

Flooding can be observed from multiple causes and sources, which may affect individually or in some combined way. To disregard the combined flood events can cause failures of flood defences (Burton et al., 2010). In publications, fluvial flooding is mostly investigated (Moncoulon et al., 2014) with more recently pluvial flooding is incoming of interest, but the combined fluvial and pluvial flooding is a very new approach in literature (Breinl et al., 2015). Furthermore, the papers have discussed the different combinations of coastal, tidal, fluvial, pluvial, and groundwater flooding; and by using procedures mostly based on Monte-Carlo analysis, the joint probability of tidal and fluvial flooding (Apel et al. 2006; Chen et al., 2010; Lian et al., 2013).

The approaches of previous papers that investigated the combined fluvial and pluvial flooding can be listed as that.

Burton et al. investigated the combined hazard of fluvial and pluvial flooding for the South East London Resilience Zone (SELRZ) in 2010. The nested modelling approach provided datasets for simultaneous analysis of pluvial and fluvial flooding. Both disaggregated rainfall data and upstream discharge were applied into the urban inundation hydraulic model to assess both pluvial and fluvial flooding. This simulation and analysis were performed by using two-dimensional non-inertial overland flow model (Burton et al., 2010).

Rainfall data was estimated by using climate projections. The methodology of the climate projections based on the UKCP09 future climate scenarios for the 2050s. The discharge was estimated by using hourly rainfall data and then, was entered into the fluvial flood model. The disaggregated rainfall data at 15-minute on a 2 km resolution, (and finer spatial-temporal resolution), was entered into the hydraulic model of pluvial flooding.

Horton Soil infiltration was applied to calculate the runoff on rural areas. Sewer drainage loss was applied to the runoff in urban areas (Burton et al., 2010).

In summary, Burton et al. (2010) investigated the combined hazard of fluvial and pluvial flooding in an urbanised catchment. Rainfall dataset was produced with consideration climate change. Combined hydraulic and hydrological modelling approach was used for simulations of flooding. The nested modelling approach was recommended to provide input datasets for both pluvial and fluvial flooding analysis.

Chen et al. (2010) investigated both pluvial and fluvial flood events in Stockbridge area in Keighley (Bradford, UK), and stated that heavy rainfall could cause both pluvial and fluvial flooding in this area because it is both an urban and settled along the route of the River Aire. They simulated combined fluvial and pluvial flood events and compared the consequences. The combined peak river water level and rainfall were assessed in this research.

Fluvial flood events with a return period of 200 years were set-up for hypothetical overtopping and breaching situations. The pluvial rainfall durations ranged from 15 minutes to 360 minutes with return periods from 1 in 2 to 100 years. The SIPSON software was used to design 1D flow in the drainage system. While UIM software was used to model 2D overland flow for the surface flow simulation. The results of the composite flood events were used to identify the dominant factor that caused flood inundations in different parts of the research area. The results showed that the combined flood extents displayed greater flood inundation areas and depths than the results of a single type of flood event.

In summary, Chen et al. (2010) studied the determination of the risk of the combined pluvial and fluvial flooding for settlements along the route of the river. Intense rainfall can cause both pluvial flood events because of the overwhelmed sewer system and can cause fluvial flooding because of the limited capacity of the river channels in urban areas. This situation is very similar to the combined flooding process in the Wortley Beck catchment as well. They recommended that the timing and the duration of the rainfall events should be considered, in addition to the peak water level in flood inundation areas of composite flood events. This approach can make the parameter of the catchment response time very significant to evaluate the rainfall and discharge in a catchment.

They recommended that the joint probability approach based on Monte Carlo could be used to analyse the combination flood risk in more detail. The main outcome of this research seems to be that the consequences of the combined flood events can be much serious than the consequences of a single type of flood event. This knowledge could be used to develop flood damage mitigation approaches much efficiently in the future.

Horritt et al. (2010) suggested two different approaches to combine flood events. These are the fully integrated approach and the map combination approach. The different flood event sources were combined, and then routed along pathways to the risk receptors in the fully integrated approach. The different sources of flooding probability can be assessed at the same time by this approach (Horritt et al., 2010). In the map combination approach, common boundary conditions of the flood events of different sources were generated and were routed separately then probabilistic flood maps were combined.

Horritt et al. (2010) aimed to combine different sources of a flood event, such as, river, coastal, surface water etc. into the single map with both the individual and combined probability of each of these events. Therefore, the outcomes, such as likelihood, extent, depth, velocities of flood events from different sources could be used by flood risk professionals, decision makers and the public to improve the flood risk assessment.

The approach of the overlapped map can have a limitation for the evaluation of the independent sources and probability. Therefore, the fully integrated approach could be very useful to evaluate risk of combination flooding.

Lian et al. (2013) investigated the effects of the combined rainfall and the tidal level in Fuzhou City, which is a coastal city. Lian et al. (2013) examined the joint impact of rainfall and downstream tidal level on flood risk in a coastal city with a complex river network. The effects of the combined rainfall and tidal levels with and without pumped flood relief systems on flood probability were assessed. Rainfall events were derived based on the 10, 20, 50 and 100-year return period and the hydrographs were estimated by using design rainfall events. A precipitation event and a typical tide event were selected and used as boundary condition for the simulation by using HEC-RAS software.

In the analysis of the results, they introduced the joint probability method to examine the relationship between tidal floods and extreme precipitation. The results showed that a high tidal level is usually accompanied by heavy rains and this causes the greatest threat in Fuzhou to be from heavy rainfall events. However, the risk of both rainfall and tidal level exceeded their threshold is very low. In this methodology, the decision for the threshold could be very critical to assess the combination of the flooding. Lian et al. (2013) recommended investigating the joint of flood probability and consequence into a single risk function in the future in detail.

Moncoulon et al. (2014) combined two independent probabilistic events involving overflowing rivers and surface water runoff due to heavy rainfall on the slopes of the watershed. They used a stochastic distribution of river discharges on the large catchments and a stochastic distribution of spatialized rainfall on the small catchments. Moncoulon et al. (2014) produced a distributed hazard model from the combined stochastic runoff–rainfall and river routing models. River overflow and surface runoff were combined with a homogeneous approach.

In this approach, to produce data for rainfall-runoff model and river routing model could be the hardest part. In addition, the length and the quality of the measured input data can be the most important part.

Breinl et al. (2015) focused on finding the days of combined of fluvial and pluvial flooding so they developed a joint probabilistic modelling framework to simulate daily peak discharge and maximum hourly precipitation in the city of Salzburg (over 30 km^2 area). Daily peak discharge was used to identify of the days of fluvial flooding, and maximum hourly precipitation was used to identify of the days of pluvial flooding. A stochastic Weather generator was used to produce daily precipitation, which was passed through a hydrological model to produce daily mean discharge, and subsequently daily peak discharge. Daily precipitation was also converted into maximum hourly precipitation data. Occurrence critical thresholds of river discharge for fluvial flooding and extreme precipitation for pluvial flooding were studied to define and to examine combined fluvial and pluvial flood in this research (Breinl et al., 2015).

The joint occurrence of fluvial and pluvial flooding was investigated by using long-term data. Breinl et al. (2015) estimated the probabilities of joint occurrence of fluvial and pluvial floods. In addition, they asked whether or not the days when fluvial or pluvial flooding occurred could be simultaneous and whether this could be analysed by using observational data. In this approach, the quality of the observed data of the flood days can be very important.

They presented a joint probabilistic modelling framework to identify the combined fluvial and pluvial flood events days. The results showed that the days of the combined floods are rare. They pointed out that to define exact catchment response times is not easy, and to determine a certain threshold for flood days can be very complicated. In addition, the land use properties in the catchments have changed since urbanisation. They recommended that future research could focus on the definition of critical thresholds to define it better.

Lastly, they mentioned that this method could be coupled with a hydraulic model to produce inundation maps and these maps could be used to assess the hazard from fluvial and pluvial flood events. This kind of approaches can be linked with the GIS tool as well to produce flood inundation maps.

Apel et al. (2015) examined the combined fluvial and pluvial flood hazard in a set of joint flood events. The events were simulated by using the combined fluvial and pluvial flood events with the same individual probability of occurrence. The research area was the Mekong River basin that is in a tropical environment. Fluvial and pluvial flooding can be seen at the same time due to heavy local convective rainfall events during the annual monsoon season. However, the fluvial and pluvial flood events were assumed independent from each other even they were observed in the same season. The probabilistic hazard maps were produced for both individual and combined hazard.

A synthetic rainfall event was added at the time of the maximum water level of the fluvial boundary for per probability level of fluvial flood scenarios, to produce combined fluvial and pluvial flood hazard maps. Maximum inundation maps were produced to display the median maximum inundation depth for different probability levels from the 5% to 95%.

In conclusion, based on the observations from the previous papers that investigated the combined fluvial and pluvial flooding, these can be said that; some research approaches consisted in rainfall data set as the input into the combined hydraulic and hydrological modelling approach. Furthermore, the combined flood events were investigated mostly to assess the hazard. Moreover, the studies mostly focused on the fluvial and pluvial events independently, also, fluvial and pluvial events were modelled separately. To model pluvial and fluvial flood events separately can cause to underestimate the hazard. Lastly, some flood extents of the different sources were observed by only overlapping the inundation maps. The assessment of the combined events by only overlapping the maps may not give realistic outcomes.

The interdependency of pluvial and fluvial flooding has been discussed for urbanised catchments to identify the relationship between fluvial and pluvial flooding in this research. The combination of the fluvial flooding from urban streams and pluvial flooding on the settlements that lie on the floodplains of these streams are the main aspects of this research.

If a dependency is determined and a relationship is assessed by fluvial and pluvial flood events in an urban stream basin, the inflow hydrograph and hyetograph must be considered with the land use change. It is crucial to examine the impact of rainfall duration, discharge from upstream basins and land use change of the floodplain on the flood processes to assess the combined flood risk.

2.2 Review of the methodology

This section presents a review of the fundamental methodology that is used to estimate and simulate the flooding in ungauged catchments.

2.2.1 Hydrological cycle in a watershed

Water evaporates by heat, followed by vapor, which transpires from plants, and then condenses, after which precipitation can occur. During this cycle, some parts of precipitation may be intercepted by vegetation and be returned back into the atmosphere by evaporation. Some parts can be infiltrated by soil and be stored in the subsurface as groundwater. Later, the excess level in the water table can be discharged to fill rivers. Some precipitation can become runoff on saturated or impermeable surfaces (Buttle, 1998).

Water balance in a watershed can be analyzed from precipitation, storage and discharge functions (Black, 1997). Analyzing the water balance is crucial for water management. The Parameters for consideration when analyzing the water balance can be agriculture, population growth, urbanization, and industrialization (Kumar et al., 2017). Climate change and change of land use can influence water quantity and the quality of the watershed hydrology, due to the relationship between water and heat transfer, in addition to the relationship between the land surface and atmosphere (Singh and Woolhiser, 2002).

2.2.2 Rainfall-runoff process in a watershed

Investigation of the amount of water in a catchment can be one of the primary scopes of the water management. This can be done by analysing rainfall (input) and discharge (output) in the water cycle (Davie, 2008).

2.2.2.1 Rainfall

Rainfall estimation is essential for rainfall-runoff modelling, watershed management, discharge estimation, and flood estimation (Keller et al., 2015). The frequency of rainfall distribution can be estimated from measured data (Guo and Adams, 1998).

Rainfall data sets can be obtained from sources such as rain gauges, weather radar, or satellites. However, each of them has own errors and uncertainty (Brauer et al., 2016).

The quality of measured rainfall data can be affected by the number of available rainfall gauge stations, its location, the elevation differences between the rain gauge and catchment, wind direction, and spatial distribution of the rainfall. It is important to consider these factors because errors in the rainfall data can cause errors when estimating the runoff (Smith, 2006; Taesombat and Sriwongsitanon, 2009; Romanowicz and Kiczko, 2016).

2.2.2.2 Areal rainfall estimation procedure

When rainfall data is measured from the rain falling at a point in a space, this is point rainfall estimation. However, mean rainfall estimation for the whole catchment is required for hydrological modelling (Lebel et al., 1987; Keller et al., 2015).

Areal rainfall can be estimated by calculating the average rainfall depths of several point rain gauges by using arithmetic mean (Thiessen method, and Isohyetal method) (Tabios and Salas, 1985). Taesombat and Sriwongsitanon (2009) found that areal rainfall depths from isohyetal techniques are smaller than those are from the Thiessen polygon technique. However, the effects of topographical variation on the rainfall data cannot be analysed using the hypsometric method, isohyetal or Thiessen polygon techniques (Davie, 2008; Taesombat and Sriwongsitanon, 2009). Keller et al. (2015) recommended using 1 km grids of daily and monthly rainfall data sets to estimate mean areal rainfall. This dataset can be used to calibrate the rainfall-runoff model.

2.2.2.3 Runoff in a watershed

Horton (1933) determined that surface runoff could be seen when rainfall events exceed the soil infiltration capacity. Green and Ampt (1911) stated that runoff could be calculated by subtracted infiltration from total rainfall. Storm runoff mechanisms can be different in each catchment (Davie, 2008).

Runoff is affected by rainfall duration, intensity, season, and catchment characteristics, such as catchment area, soil porosity, soil moisture, and land use material (Tarboton, 2003; Davie, 2008). Effective runoff can be calculated by subtracting hydrological loses from total rainfall. These losses could be caused by evaporation, depression storage loss, and infiltration losses (Guo and Adams, 1998; El-Kafagee and Rahman, 2011). Total infiltration loses consists of initial soil wetting and throughout the duration of the runoff event (Guo and Adams, 1998). Soil infiltration capacity can be affected by humid air conditions as well (Beven and Kirby, 1979).

2.2.3 Flooding in a watershed

Changes in water balance can cause flooding in a watershed. The reasons could be prolonged and intense rain, snowmelt, insufficient saturated surface, flood defence failure, or a combination of these reasons (Pilgrim and Cordery, 1993).

2.2.4 Flood risk

The flood risk must somehow be identified to improve the protection of land and communities in a catchment against flooding. Helm (1996) pointed that risk can be determined by analysing probabilities and consequences. Jones et al. (2004) determined the risk by analysing probabilities and consequences. Further, Pitt (2008) defined the flood risk as combining the probability with the potential negative consequences of the flood event.

Lastly, Chen et al. (2013) added that these two primary components must both be assessed properly in order to enable a full analysis of the risk of flooding. In summary, likelihood and the potential effects of flooding should be clearly understood to manage the flood risk and reduce the adverse impacts of flood events (Pitt, 2008).

2.2.5 Land use change and flooding

Land use change due to the human activity such as agricultural techniques (deforestation) and urbanization (population, industrial, residential buildings) in a watershed can have a significant impact on streams, rivers, and wetland (Guo and Adams, 1998). Urbanization could increase the direct runoff. The increase of the overland flow can increase the discharge. In addition, impervious areas of the watershed cause both a quick response to storms and rapid fluctuations in the flow (Weng, 2001; Shi et al., 2007; Marshall et al., 2009). This kind of water movement with high rainfall intensity in a watershed can cause increased flooding events (Cheng and Feng, 1994).

Land use change has an impact on downstream flood risk. Pattison et al. (2009) pointed out the timing and magnitude of the discharge from sub-catchment can have a significant impact on downstream flood risk. When outfall from a highly developed sub-catchment enters into the stream, the river water level can increase. In addition, populations tend to live closer the rivers, so urbanization can cause a reduction of floodplains and can change the balance of the river ecosystem and floodplains. As results of these processes, pluvial flooding in a catchment, and fluvial flood risk on the downstream of the catchment can be observed (Hayes and Young, 2006; Chen et al., 2010; Kummu et al., 2011; Jha et al., 2012). Therefore, both pluvial and fluvial flooding can be observed in the urban areas due to impervious surfaces and rainfall event (Breinl et al., 2015). Lastly, the surface runoff can be managed by using some land-use management practices and supportive infrastructure such as SUDS in urbanised catchments.

2.2.6 Flood risk management

Flood risk management approaches can be applied to decrease adverse effects of flooding. Some flood risk management approaches can be used to assess flood hazards, and to prepare effective flood resilience tools (Apel et al., 2015).

The water balance can be protected by using some land-use management practices and supporting infrastructure such as SUDS in urban areas. The estimation of flood discharges of a given return period and extent of a flood event are required to design flood defences, to improve flood resilience and to update a flood elevation scheme (Fernández and Salas, 1999; Smithers, 2012). For instance, urbanisation can make the surface runoff faster or to use of SUDS can make the surface runoff slower in the catchment.

2.2.7 Flood frequency analysis

Flood frequency analyzes the relationship between flood magnitude and annual exceedance probability so flood defense structures can be designed (Abdo et al., 2005). Return period determines the magnitude of a flood and can be used to define flood frequency for a certain probability (Smithers, 2012). Bedient et al. (1948) defined the return period as an annual maximum event that has a recurrence interval as years (T). The return period is calculated as T return = 1/ (exceedance probability) (Urías et al., 2007). An annual maximum event has a return period (or “recurrence interval”) of T years if its magnitude is exceeded, on average, every T years (Fernández and Salas, 1999).

Flood frequency can be analysed and its distribution produced for a catchment when there are a sufficient record of flood flows, and rainfall data (Romanowicz and Kiczko, 2016). When there is not sufficient flow data of the study site, regional method can be used to produce the flood frequency from a number of gauged basins (pooled method), or rainfall data can be used as intensity/ duration/ frequency curve or storm events can be designed (Blazkov and Beven, 1997; Abdo et al., 2005).

2.2.8 Flood estimation

Flood risk estimation may be required to design and improve flood management tools (Krupka et al., 2007). There is wide range of approaches to estimate flood in the literature but selecting methods may depend heavily on the purpose, availability of sufficient measured rainfall and flow data of the research area. The quality and quantity of these data sets can also have a very significant impact on the methodology. If high quality and sufficient length streamflow records are available, the frequency, location, magnitude, and extent of the flood event can be estimated directly from the data. However, sufficient records of flow data are rarely available. In these cases, flood estimation can require input data for initial and boundary conditions of the watershed (Krupka et al., 2007). Therefore, rainfall data, catchment characteristics, and flow routing models can be the primary parameters for flood estimation. Flood estimation can be used to present the watershed response to rainfall input.

Thus, a relationship between input, rainfall dataset (hyetograph, rainfall depth, intensity) and output (runoff volume, peak discharge rate) can be established (Falter et al., 2015; Romanowicz and Kiczko, 2016).

Simulation of the water movement on the surface and in an open channel can be required for flood estimation in a watershed, and hydrological models can be used for the simulation (Yu, 2002). Flood processes in rivers and urban areas can be simulated and described in time and space by conceptual and mathematical models. Thus, catchment hydrological responses can be predicted (Guo and Adams, 1998: Yu, 2002). For example, the upstream flow data can be put in a mathematical model to estimate downstream hydrograph. Routing model procedure is used to determine the flow hydrograph at a point on a watershed from a known hydrograph upstream. This procedure could be applied as a lumped approach to model the entire catchment, as a semi-distributed model by modelling sub-catchments of the basin or as a distributed model by diving the catchment into the grids (Moore, et al., 2007; WMO, 2009). Lumped models can be used in hydrological assessments and fluvial flood forecasting of the whole drainage basin. Lumped (hydrologic) model is used to calculate flow at time duration for a particular location in the catchment. Parameters of the lumped models do not change in space. Distributed (hydraulic) model is used to calculate flow movement at space and time duration of sub-catchments of the basin. The advantage of applying a distribution approach is that the rainfall model can assume the events are independent and realistic (Moore, et al., 2007; WMO, 2009).

Moreover, rainfall-runoff models with a dynamic model can be used to investigate the relationship between river flow in a cross-section of interest and earlier rainfall events over this cross-section in the basin (WMO, 2009). Instead of using sole large-scale hydrological models, rainfall-runoff models with a hydrodynamic model can be used for better flood estimations. Large-scale hydrological models usually use simple flow routing models that focus only on the flood wave delay and attenuation. They cannot deal with some of the hydrodynamic processes such as backwater effects, floodplain storage effects and 2D flood extent (Paiva et al., 2011). However, hydrodynamic models can require much detailed information about boundary and initial conditions, such as; land use material, soil type, and hydraulic properties (Yu, 2002; Paiva et al., 2011).

Continuity and momentum equations can be used calculations of the flood estimations in a watershed (Yu, 2002).

The relationship between storage and flow is determined empirically by Muskingum method (McCarthy, 1938; Moore et al., 2007).

Equation 2.1: The Muskingum Routing the continuity equation

$$I - Q = dS/dt$$

Where in Equation 2.1 (McCarthy, 1938); I is input, Q is output, S is storage.

Complete dynamic routing determines flows and water-surface elevations accurately by using unsteady flow situations known as the Saint Venant equations (Patowary and Sarma, 2017).

The momentum conservation equation of the Saint Venant contains Dynamic model, Diffusion model and Kinematic model (WMO, 2009).

Equation 2.2 Dynamic Model

$$\frac{1}{g}\frac{\partial h}{\partial t} + \frac{v}{g}\frac{\partial v}{\partial x} + \frac{\partial h}{\partial x} - S_O + S_f = 0$$

Where in Equation 2.2: t is Time; x is distance through the channel (m); g is Acceleration due to gravity (m/s^2); S_o is the bottom slope of the channel; S_f is Friction Slope of the energy line.

Equation 2.3 Diffusion Model

$$\frac{\partial h}{\partial x} - S_O + S_f = 0$$

When the time variation of inflow and the spatial variation in velocity are neglected, this approximation is known as the diffusion model. The diffusion model can be used on rivers with smaller slopes (WMO, 2009).

Equation 2.4 Kinematic Model

$$-S_O + S_f = 0$$

When the momentum equation has a balance between the forces of gravity and friction, this approximation is known as the kinematic model.

The kinematic and diffusion models can be used to describe overland flows and flows in streams. However, the kinematic model cannot simulate backwater effects from lateral inflows (WMO, 2009).

On the other hand, fully distributed models are often computationally expensive and data demanding. In addition, partial differential equations (PDEs) are used to represent hydrological processes by the physical distributed models (WMO, 2009). The partial differential equations can be solved by using the numerical scheme and a finite difference scheme (Yu, 2002). A linear and implicit finite difference numerical scheme was developed by Chen (1973), and the Preissman scheme was developed by Cunge et al. (1980) (Paiva et al., 2011).

2.2.9 Flood modelling

Flood modelling software packages are required to design appropriate mitigation measures, for flood risk assessment in urban areas at local, street, and catchment-scale. Flood risk can be assessed by defining the flow paths, ponding areas, and water depth values in the research area. These modelling tools can be used to convert the overflow to water level (m AOD) and flow (m^3/s) values along the flooding pathway. Thus, high-risk inundation areas could be identified, water depths (m) and peak flows (m^3/s) can be computed (Evans et al., 2004; Paiva et al., 2011). The 1D simulation can be performed using software packages such as Info works-RS, Flood Modeller Suite, Mike-11, and HEC-RAS. Two-dimensional shallow water equation models can be used for inundation prediction in flood risk management, through the application of commercial packages such as TUFLOW, MIKE FLOOD, Flood modeller Suite (ISIS) 2D, Info works 2D and SoBEK.

One-dimensional (1D) hydrodynamic river models have been used to solve the full Saint Venant equations since 1980 (Cunge et al., 1980). The advantages of one-dimensional models can be fast in the calculation and they require fewer bathymetry data (Villanueva and Wright, 2006). However, this approach could result in a very simple model to represent floodplain (Paiva et al., 2011).

To simulate fluvial flood extents in detailed, the one-dimensional and two-dimensional models can be linked to combine the river channel and floodplain. Hence, the river channel is displayed with nodes and floodplain are determined by light detection and ranging (LiDAR) data (Villanueva and Wright, 2006). The movement of the fluvial floodwater is expected towards the floodplain areas (Néelz, 2009). A rainfall–runoff model with a dynamic link can be used to observe the interactions between flows in the main channel and floodplain. In this approach, the hydrological model is linked to both the 1D flood routing model along and 2-D flood inundation model. This approach can be applied to combine 1D river channels with 2D overland flow hydrodynamic models (Evans et al., 2007; Chen et al., 2010). WBM Oceanic Australia and The University of Queensland developed a 2D/1D dynamically linked modelling system in 1990 (Syme, 1992). 2D solutions can solve the two-dimensional depth-averaged shallow water wave equations, so that interaction between river and floodplain can be simulated accurately (Syme et al., 1999). The value of water depth at each cross-section is taken from the 1D model and is overlaid onto a DEM by 2D model with using GIS software to simulate flood inundation extent (BMT WMB, 2016). Thus, the size of the 2D domain is smaller than the research basin therefore; model run times can be shorter (Engineers Australia, 2012).

The flow in the streets is mostly one-dimensional, such as overland flows and pipe flow whereas, in reality, flows by junctions can be three-dimensional. However, simulation of urban runoff can be done by using a 2D modelling method on a catchment scale analysis (Mignot et al., 2006). In addition, a two-dimensional model can combine topographical data such as; DEM, and hydraulic principles to determine flow movement in the channel and on the floodplain surface (Bates and De Roo, 2000; Engineers Australia, 2012). Thereby, the two-dimensional model can be used to simulate complex flow pathways, flood depth, velocity, and direction of urban surface flow (Morris et al., 2009). Additionally, the impact of different land-use scenarios on these results can be analysed to investigate flood risks (Evans et al., 2007). Outcomes of these simulations, such as the water depth, velocity, flood levels, and peak flow can be computed at each computational node for each time step (Bates and De Roo, 2000).

2D free surface models can represent water flow in a horizontal and can be used for many flood events, such as; fluvial, direct rainfall and urban flood modelling. However, the use of full 2D hydrodynamic models in simulations and predictions is still relatively expensive due to requiring long computer run time and detailed, high-resolution topographic data (Syme et al., 1999; Zhang, 2015).

However, Floods Directive requires using flood risk mapping to analyse flood hazard in detail, to identify flood risk areas and to develop flood risk management plans (Martinkova, 2013). Therefore, to manage flood risk efficiently, flood risk assessment should be done strategically by producing and analysing flood risk maps, flood hazard maps, and flood inundation maps.

Flood risk maps can be derived starting from the design rainfall based on observed rainfall events followed by a rainfall–runoff and flow routing models. Flood risk maps are estimated using 1-D or 2-D hydrodynamic models with flood wave input data (Martinkova, 2013: Romanowicz and Kiczko, 2016). In addition, the GIS-based algorithms have been developed to extract the parameters from DEM for hydrodynamic models (Paiva et al., 2011).

2.2.10 Flood estimation methods in ungauged catchments

Measured flow data is required to model flood events, and to estimate flood risk. However, sufficient observed flow records may not available for the site of interest (Smithers, 2012). Therefore, rainfall-based flood estimation methods have to be used. These are continuous simulation or event–based approaches (Romanowicz and Kiczko, 2016). To select a suitable method of estimating stream flow; catchment characteristics, quality, and quantity of the measured rainfall data are the primary concerns. If there are sufficient quality and quantity rainfall historical or stochastic rainfall data sets, flood estimation can be performed by using continuous simulation. The continuous simulation can be used to observe water balance and to estimate discharge in a watershed (Boughton and Droop, 2003). For instance, catchment behavior at the evaporation, transpiration, infiltration, interception, and storage stages of the water cycle can be observed in the catchment.

Whereas, this simulation requires rainfall data sets and computation time for a long period.

On the other hand, the event-based method can be applied to estimate flood (Faulkner and Wass, 2005). Guo and Adams (1998) proposed the event-based probabilistic models as an alternative to continuous simulation models. They are user-friendly and preferred for real-time operational applications in Southern Europe (Tramblay et al., 2012).

Moreover, event-based uses probabilistic approaches to estimate runoff volumes and peak discharge for specified return periods. Probabilistic approaches can produce results for reinsurance brokers and modelling companies.

Moreover, to design urban drainage facilities, flood defenses, and to improve flood resilience, event-based probabilistic models can be used as an alternative to the Numerical hydrologic model (Guo and Adams, 1998).

Flood events can be estimated from a design rainfall event, which can be designed for a given return period in ungauged catchments (Faulkner and Wass, 2005). The limitations of this approach are, firstly, return period is assumed the same as the flood event. Whereas, the rainfall return period could be bigger than flood return period. Secondly, this method could overestimate design flows in some catchments. Even after similar rainfall events, different magnitude of flood events can be observed due to the soil moisture capacity before and during the rainfall event (Romanowicz and Kiczko, 2016). In addition, by using this method, only single peak flow can be estimated and flood estimation is performed for a fixed duration (Faulkner and Wass, 2005).

To simulate flood inundation scenarios in ungauged catchment, rainfall data set is entered into a rainfall–runoff model with a flow routing model. Faulkner and Wass (2005) generated rainfall series and used the rainfall–runoff model to compute inflows. These inflows were used as an input to a 1-D hydraulic model. Moreover, Falter et al. (2015) added a flood loss model in this approach (Romanowicz and Kiczko, 2016). However, these studies showed that model simplifications are necessary to run the simulations in an acceptable computational time (Romanowicz and Kiczko, 2016).

Hence, simple flow routing methods can be used with hydrological models, these methods can still provide reasonable outputs with reasonable input data (Paiva et al., 2011). A similar integrated approach to flood risk assessment was presented by McMillan and Brasington (2008). Falter et al. (2015) extend the approach by presenting the complete flood risk chain, apart from rainfall generator, rainfall–runoff, and flow routing models. Additionally, a flood loss model was included (Romanowicz and Kiczko, 2016).

A rainfall based flood estimation approach consists of rainfall estimation and flow routing models. Rainfall data is used as an input to a rainfall–runoff model.

Rainfall intensity can be produced from the intensity/duration/frequency analysis (IDF) to produce peak flow. Alternatively, rainfall depth values and durations can be used to produce a hydrograph from a long-time series rainfall data set.

Using flood frequency analysis on this rainfall data in a flow routing hydrological model allows runoff as peak flow or a discharge hydrograph to be calculated for a required return period. Finally, this can be used in a hydrodynamic model so that flood risk maps can be produced (Blazkov and Beven, 1997; Romanowicz and Kiczko, 2016).

2.2.10.1 Rainfall estimation methods

When streamflow data is not available at the subject site, flood events can be designed from storm events in ungauged catchments. Rainfall event is designed from rainfall depth, intensity and return period of the storm (Romanowicz and Kiczko, 2016). Rainfall frequency estimation can be done by using depth/duration/frequency (DDF) curves (Svensson and Jones, 2010). Rainfall depth parameter can be used as a function of duration for given return periods or probabilities of exceedance (Overeem et al., 2008)

Firstly, annual maximum precipitation depth can be calculated for a given duration for each year. Next, frequency analysis can be performed to derive design precipitation depth for different return periods by using the Extreme Value Type I (EV1 distribution), or Gumbel distribution (Chow et al., 1988).

The frequency is determined as return period (T); this parameter represents the average length of time (year) between rainfall events that equal or exceed the design period. The return period is fundamental for depth-duration-frequency curves, to calculate the depth of the rainfall event (Fitzgerald, 2007). The frequency of occurrence of total rainfall may depend heavily on the length of rainfall duration, and season (Shaw et al., 2011). Finally, after plotting depth versus duration for different frequencies, the rainfall depths (D) are converted to intensities (Chow et al., 1988). To estimate the flood frequency distribution from rainfall records may require the estimation of an effective runoff coefficient or percentage runoff for each storm and this is a particularly difficult problem for ungauged catchments (Blazkov and Beven, 1997).

2.2.11 Loss model

The magnitude of loss is dependent on a number of catchment parameters such as topography, vegetation, soil moisture conditions, and storage (El-Kafagee and Rahman, 2011). In design flood estimation, the initial loss and continuing loss model are calculated to obtain surface runoff (El-Kafagee and Rahman, 2011). Initial and continuous loss parameters are developed with some assumptions in rainfall-runoff models of event-based approaches. Initial loss is the amount of rainfall that occurs before the start of surface runoff, while continuous loss is assumed the average loss rate throughout the remainder of the rainfall event. Infiltration starts after surface depressions are filled. Runoff starts after initial soil wetting is satisfied by infiltration. Initial soil wetting is accepted as the same during the rainfall event (Guo and Adams, 1998). Initial soil moisture conditions can depend on the antecedent soil moisture (Tramblay et al., 2012).

Loss models in the design of flood estimation might not represent the spatial and temporal distribution of the actual loss in a catchment. Rainfall could not be uniform during the event over the entire catchment in space and time. Similarly, Antecedent moisture conditions should not be assumed as fixed values for the whole catchment (Blazkov and Beven, 1997; El-Kafagee and Rahman, 2011).

2.2.12 Flood frequency analysis for ungauged catchments

The analysis of flood frequency of an event is an important concept. If the measured rainfall and flood data (annual maximum series) are sufficient, the magnitude of flood events can be estimated from the measured data for a catchment. However, in ungauged catchments, the magnitude of flood events can be estimated from measured data of a similar catchment as the subject ungauged catchment. If the characteristics of two catchments are similar and have similar rainfall events, flood events could have similarities.

If the subject catchment in the UK does not have sufficient measured flow data, by using pooling approach of FEH statistical flood estimation method, flood frequency analysis can be performed for this catchment. In this method, measured flood data of the catchment with similar characteristics are used. Thus, flood frequency curve of the ungauged subject site can be plotted and peak flow values for different return periods can be estimated (Cunderlik and Burn, 2002; WHS, 2009; Kjeldsen, 2010).

Calculation of flood frequency can be used to gain a better understanding of the relationship between flood magnitude and rainfall intensity in ungauged catchments. This knowledge can contribute to design flood resilience tools and assessing the magnitude of the flood events in detail at ungauged sites (Viglione and Blöschl, 2009).

To investigate the probability of peak flow values in the ungauged Wortley Beck catchment, the pooled method of statistical procedures for flood frequency estimation in ungauged catchments was used. Statistical Flood estimation procedure can be one of the primary techniques to calculate the frequency of peak flow.

2.2.12.1 Statistical flood estimation method

Index flood method can be used to create flood frequency curves in this research like the Flood Estimation Handbook guideline. In addition, improved statistical procedures and the index flood methods have been selected from hydrologists and engineers for design flood estimation in the

UK as well (Institute of Hydrology, 1999; Kjeldsen and Jones, 2007; Kjeldsen and Jones, 2010).

Briefly, the steps of producing flood frequency curve are:

1. Estimation of the QMED (the index flood),

2. Definition of a pooling group for the catchment of interest,

3. Application of the urban adjustment equation to the QMED rural,

4. Estimation of an appropriate flood growth curve (z_T),

5. Production of the flood frequency curve,

2.2.12.2 Estimation QMED (the index flood)

The index flood can be defined as the median annual maximum flood (Kjeldsen and Jones, 2007). QMED (m^3/s) has a two-year return period (Robson and Reed, 1999).

QMED is used to produce the flood growth curve. QMED can be estimated from either AM data, and POT data if there are sufficient measured flood data, or QMED can be estimated by using the catchment descriptors equation (Kjeldsen and Jones, 2007; WHS, 2009).

Measured flood data of gauged catchments in the pooled group is used for the subject-ungauged catchment. The gauged catchments in the pooled group are selected according to their similarity to the ungauged subject catchment descriptors (WHS, 2009). The catchment descriptors parameters are the catchment area (AREA), standard average annual rainfall (SAAR), flood attenuation by reservoirs and lakes (FARL), and floodplain extent (FPEXT) (WHS, 2009). Gauged sites in the pooled group are recommended to have at least 5 years (preferably 8 years) of AM data, to be larger than 0.5 km^2 and the $URBEXT_{2000}$ value of the Gauged sites in the pooled group should be lower than 0.030. In addition to these, similar flood history, and flood seasonality factors can be assessed (Robson and Reed, 1999; Kjeldsen et al., 2008; WHS, 2009). Catchments in the pooled group can be selected by using WINFAP-FEH 3™ software.

After calculation $QMED_{rural}$ from catchment descriptors equation, it is recommended to adjust $QMED_{rural}$ value by using a donor site.

This adjustment can be accomplished by using the data transfer method (Kjeldsen et al., 2007; WHS, 2009). The donor catchment is recommended to be nearby the subject catchment, such as by the same river, upstream or downstream of the subject site and have good quality flood data (Robson and Reed, 1999; Kjeldsen et al., 2008; WHS, 2009; Kjeldsen and Jones, 2010).

Lastly, a flood growth curve (z_T) was constructed by using the pooling-group data to derive a flood frequency curve because the flood frequency curve can be obtained by multiplying with the z_T by QMED (Kjeldsen et al., 2008; WHS, 2009). A flood growth curve is created by fitting a distribution to the observed AM data (WHS, 2009). This distribution is selected by using the goodness-of-fit measure (Z).

The Generalised Logistic distribution and the Generalised Extreme Value distribution could give the best fit for the UK data (Robson and Reed, 1999; Kjeldsen et al., 2008). Finally, a flood frequency curve is plotted. A flood frequency curve can be used to define the relationship between peak flow (Q, m^3/s) and the return period (T, year) (WHS, 2009).

Chapter 3 Fluvial flood event modelling

3.1 Introduction

River flooding (Fluvial flooding) is the most frequent, a harmful and an effective natural threat in the worldwide (Field et al., 2012; Jongman et al., 2012; Tanoue et al., 2016). A river flooding can be seen, when the riverbank is overwhelmed, and the flood defence systems are insufficient, so the water overflows onto the floodplain.

The initial reason for the river flooding can be intense discharge at the outfall of sub-catchment because of the high and fast runoff volumes in the sub-catchment. The reason for the great magnitude of runoff volumes in a sub-catchment can be an intense rainfall event, ice melting, impermeable surfaces, and the failure of drainage systems (Chen et al., 2010; Jha et al., 2012). As consequences of climate change, and urbanisation in the sub-catchments, high discharge can be observed. Thus, fluvial flooding can be observed frequently and can have a great magnitude at the downstream area (Putro, 2013). Therefore, the downstream area can have a potential to be inundated with fluvial floodwaters. Furthermore, under natural conditions, wetlands are located on the floodplains (riverine wetlands) therefore the adverse effects of flooding can be mitigated (Nghia and Chau, 2000; Old et al., 2008). However, population increases and settlements can be found on the floodplains (Uyen, 2002; Hung et al., 2010; Kummu et al., 2011). Consequently, fluvial flood frequency, flood event duration, and magnitude of flooding can be affected by land use change in the sub-basins (Old et al., 2008). Land use assessment could have a priority to mitigate discharge and to decrease the flood risk at the downstream location (Pattison et al., 2010; Putro, 2013).

The aim of this chapter is to assess the fluvial flood risk for the Lower Wortley Beck. The effects of the inflows from sub-catchments of the Wortley Beck catchment on fluvial flood risk of the Lower Wortley Beck were assessed in this research.

The suitability of the Lower Wortley Beck with this research

The sub-catchments of Wortley Beck catchments are Farnley Wood Beck and Farnley Beck basins. The locations of these sub-catchments can be found in Figure 3.3. Farnley Wood Beck and Farnley Beck are Critical Ordinary Watercourses. Critical Ordinary Watercourses (COWs) represent that this area has a risk of flooding (Atkins, 2004). In addition, Flood Map for Planning (Rivers and Sea) (Environment Agency, 2017) displays that the Lower Wortley Beck is in the Flood Zone 3 (Figure 3.1). Flood Zone 3 means that the area could have the 1 in 100-year or greater chance of the fluvial flood event for each year (Environment Agency, 2017).

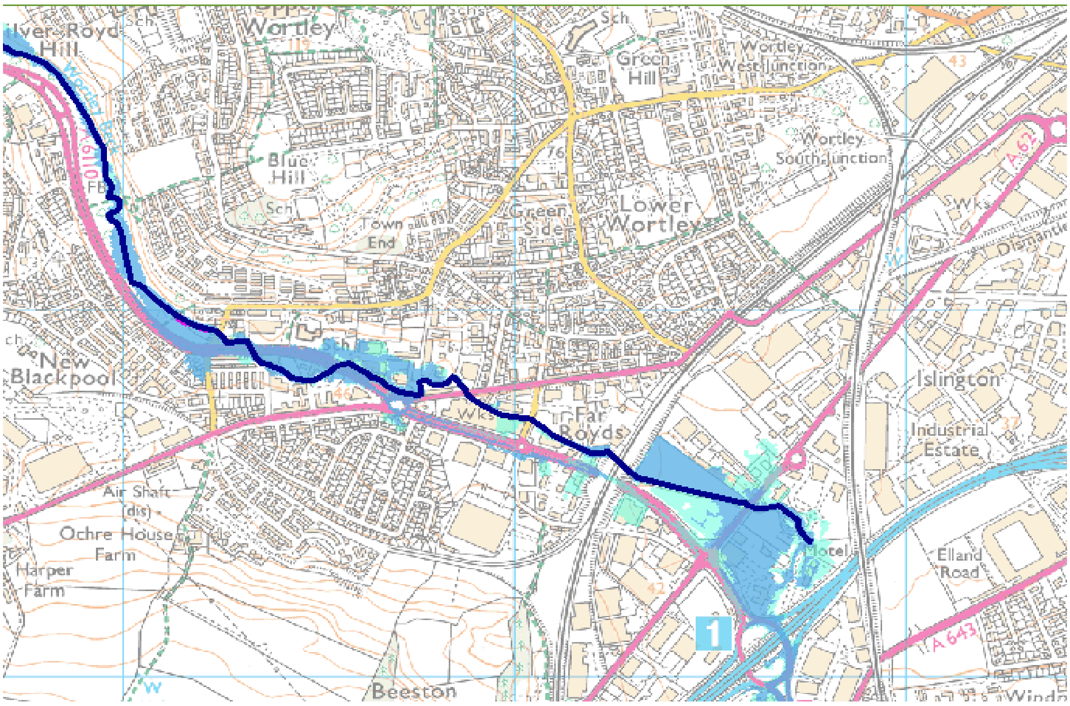

Figure 3.1 Flood zone 3 area of the Lower Wortley Beck catchment at Flood Map for Planning (Rivers and Sea) (Environment Agency, 2017)

In addition, valuable properties have been building in the flood-vulnerable locations in the research area.

Research Steps

The fluvial flood risk was assessed by investigating the impact of inflows from sub-catchments on the Lower Wortley Beck area. The inflows were predicted for various ratios of the impermeable surfaces of the sub-catchments and rainfall durations on the sub-catchments. These inflow hydrographs were integrated with the 1D/2D hydrodynamic fluvial flood model to assess the downstream flood risk.

1. Fluvial flood extent maps of the Lower Wortley Beck area were produced.

Fluvial flood extent was predicted for 1% AEP flood event and 1990 year of URBEXT values of the sub-catchments.

2. The effects of the land-use change in the sub-catchments on the fluvial flood risk were assessed.

The impacts of the ratio of impermeable surfaces of the sub-catchments on the discharge at outfalls of the sub-catchments and flood extents at the Lower Wortley Beck area were investigated in this section. This assessment was performed by changing the value of the URBEXT parameter of the sub-catchments.

3. The effects of rainfall duration on the fluvial flood risk were assessed.

The impacts of the rainfall duration on the discharge at outfalls of the sub-catchments and flood extents at the Lower Wortley Beck area were investigated in this section. The length of the rainfall events was changed from 0.5 hr. to 1 hr., and then to 6 hr.

3.2 Methodology

Fluvial flood model of the Lower Wortley Beck is explained in this section.

In the UK, as a part of the fluvial flood risk management, river channel, hydraulic structures can be modelled using the 1D hydrodynamic software such as Flood Modeller Suite software (Evans et al., 2007). Flood Modeller Suite 1D model is one of the preferred simulators to investigate the hydraulic effect, flows and water levels in open channels and estuaries such as bridges, culverts and other hydraulic structures (Wangpimool and Pongput, 2011).

Flood Modeller Suite 1D hydrodynamic model was produced by CH2M HILL /Halcrow (UK). Flood Modeller Suite software can be used for both unsteady and steady flow with options that include simple backwaters and flow routing (Wangpimool and Pongput, 2011). Flood Modeller Suite software uses an implicit finite difference method called the Preissmann implicit scheme to solve the De Saint Venant Equation in unsteady flow. Flood Modeller Suite software uses adaptive time-stepping methods to manage run-time and model stability (Wangpimool and Pongput, 2011).

To simulate fluvial flooding, the Environment Agency investigated a tool to link 1D to 2D between Flood Modeller Suite and 2D solvers. For instance, embankments and structures including culverts can be displayed in one dimension, and the flood extents can be represented in 2D domains. In addition, computational run time can be reduced (Evans et al., 2007). Hydraulic structures such as the drain, creek, and rivers are not recommended to represent by the 2D cells. They are better represented by 1D cross-section. The 2D cells can be shown as wet and dry at any point during a simulation (Syme, 2001). Moreover, the 2D solution is used to manage momentum for downstream controlled regimes by switching with upstream controlled regimes (weir or supercritical flow) (BMT WMB, 2010). Lastly, 2D models are used for flow and inundation patterns in floodplains, coastal waters, estuaries, rivers, and urban areas. Among of these 2D solvers, TUFLOW and DIVAST were recommended to present reasonable predictions of flood extents (Evans et al., 2007).

Advantages of this dynamically link with TUFLOW or DIVAST are that river and floodplain can be schematisation easily. The TUFLOW is specifically adjusted for these flood simulations (BMT WMB, 2016). TUFLOW is selected due to its strengths over finite element schemes in rapid wetting and drying, and its unique and flexible dynamic links with a 1D scheme (Syme, 2001).

The Flood Modeller Suite (CH2M) and the TUFLOW (BMT WMB) software can be classified as suitable to simulate flood events in literature such as Liang et al, 2008; Delis and Kampanis, 2009 (BMT WMB, 2010); Zhang, 2015. For instance, 1D channel model and two-dimensional (2D) floodplain hydrodynamic model (Flood Modeller Suite linked TUFLOW) was constructed by Jacobs for the flood modelling and mapping of the Thames River.

Flood Modeller Suite link to TUFLOW produces depth, velocity, and water level outputs and that can be imported into GIS software to produce flood inundation maps (BMT WMB, 2010). This approach is suitable to identify flood zones, flood hazard and water depth so that the results can be used for strategic level decision-making and development planning.

In conclusion, in this research, a 1D / 2D finite difference numerical model (Flood Modeller Suite/TUFLOW hydrodynamic model) was preferred to investigate the flood flow routing across the floodplain. This approach was considered suitable given the perceived mechanisms of flooding to the site and in the study area.

3.2.1 Setting-up the 1D/2D fluvial hydraulic model

The ReFH FSR/FEH rainfall-runoff method and a one-dimensional (1D) link two-dimensional (2D) hydrodynamic model were used. Flood Modeller Suite 1D (CH2M HILL) 3.7.0 version was linked to the TUFLOW 2D (BMT WBM) Build 2013-12-AD-ISP-w64 version software.

Hydraulic structures and initial conditions of the river channel were constructed by Environment Agency. However, the model was updated and calibrated during this research.

The river channel of Lower Wortley Beck was linked to the domain of the Lower Wortley Beck. Wortley Beck sub-catchments were integrated with the model by using inflow hydrographs.

1. The estimation of the inflow hydrographs

The inflow hydrographs were entered into the model. These were produced by using the ReFH rainfall-runoff method. The inflow hydrographs presented the discharge from Farnley Beck and Farnley Wood Beck basins into the Lower Wortley Beck.

2. 1D Flood Modeller Suite Model

One-dimensional river flow was run unsteady. 1D Domain time step was 1 second.

3. 1D link 2D

One-dimensional Flood Modeller Suite software was linked to two-dimensional TUFLOW software by control file (.tcf). 2D Time step was 2 sec. 2D TUFLOW model controlled geometry, boundary condition, and land-use categories (materials) in the 2D Domain. Geometry was used to define river channel and flood extent area. 2D domain elevation information was obtained from topographical data.

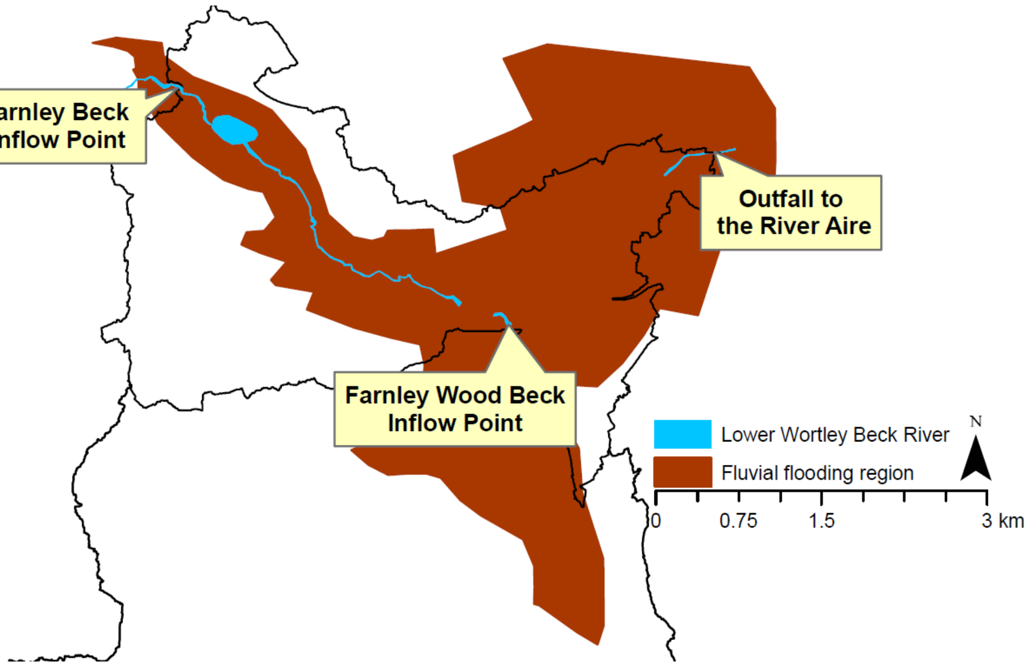

Figure 3.2 The fluvial flood model region

Figure 3.2 displays that the inflow points of the Lower Wortley Beck, and the 2D domain area of the Lower Wortley Beck. The inflow points are the outfalls of the Farnley Wood Beck and Farnley Beck sub-catchments. The length of the river channel was measured nearly 3.5 km in the research area.

Topographic and bathymetric data were used in the construction of the hydraulic model and in the production of flood maps. 2D domain elevation information was obtained from topographic data. Light Detection and Ranging (LiDAR) data was used to generate digital elevation map (DEM) by using GIS software (Figure 3.3). Grid resolution of the data is 2m and it was taken from Environment Agency data. Figure 3.3 displays the surface elevation of the Lower Wortley Beck area. Cell size of the model was 8 metre for this simulation.

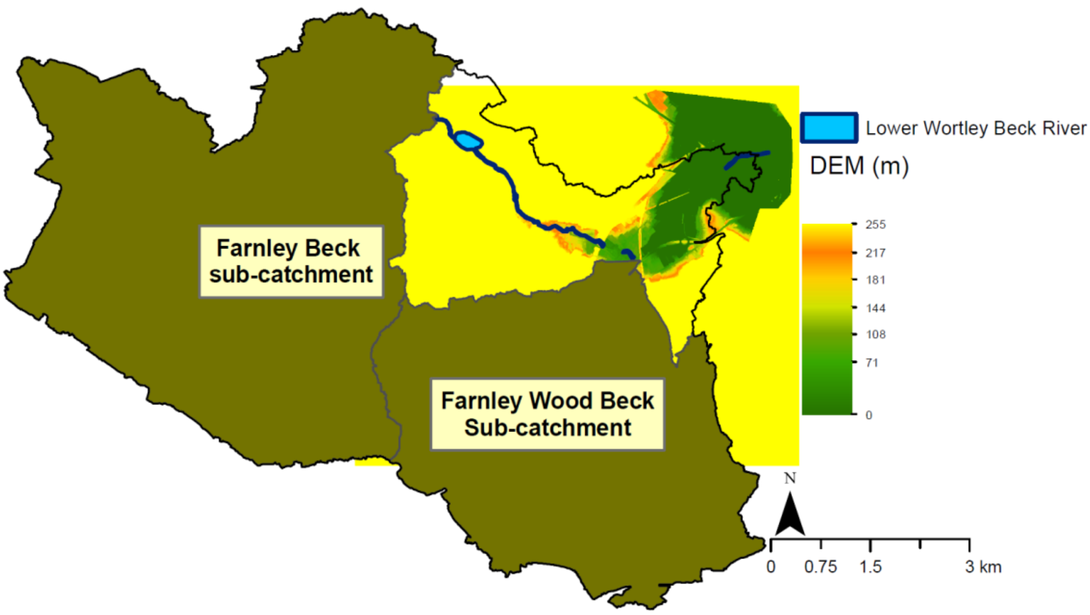

Figure 3.3 Geometry of fluvial flood modelling

The material file was used to define roughness. Manning`s n values were applied for each surface material in the research area. Material values were defined for both river channel and along the right and left floodplains of the Lower Wortley Beck (Table 3.1). The values were determined by the Environment Agency in the 2003 (summer) topographic survey (Atkins, 2004). The values were selected according to Table 4.8 in French (1985) (Atkins, 2004). Values were selected between 0.030 and 0.045 for the channel (Atkins, 2004). Values of Manning’s n (Table 3.1) for the 2D TUFLOW domain of the floodplain have been schematised based upon OS

1:10000 mapping of the model area, aerial photography and Google Street view and site walkover (Atkins, 2004). The upstream area of the Wortley Beck catchment was observed mainly rural in nature and some grassed fields were found on the floodplains. The downstream area of the Wortley Beck catchment was observed mainly urbanised. A mixture of grassed banks and impermeable surfaces were seen on the floodplains in this area (Atkins, 2004; Jepps, 2011).

Table 3.1 Manning's roughness (n) values of the materials

n	Materials
0.04	Grass
0.06	Dense trees
0.05	Fence shrubs
0.035	Gravel road
0.025	Footpaths and paved areas (roads)
0.05	Hard surface, standing areas, work yards
0.04	Open Carparks
0.20	Multi-storey carparks
2.00	Buildings

3.2.2 Flood movement equations in the 1D/2D Fluvial Model

Flood Modeller Suite hydraulic model was used to model along the river channel. In order to represent the river channel, nodes were used. The types of the nodes displayed the hydraulic units such as river section, spill, bridge, and conduit. Watercourses, bridges, culverts, weirs, and rail embankments etc. were investigated from field survey and were inserted into the model. Hydraulic structures of Lower Wortley Beck were constructed by Environment Agency in this research.

1. Spill

The Spill unit was used to calculate the flow over an irregular weir in this model (Figure 3.4). Fundamental knowledge can be read from “A mathematical model of overbank spilling and urban flooding” by EP Evans and PH von Lany (1983).

Figure 3.4 Weir Spill (Atkins, 2004)

Equation 3.1The weir equation for free flow used in the Spill

$$Q = C_d \; bh1.5$$

Where in Equation 3.1; b is the width of spill section; h is inverted elevation as a function of time t (above datum); C_d value can be 1.85 for sharp crested weirs and 1.7 for round nosed horizontal-crested weirs (Flood modeller, 2017).

2. Floodplain flow

Floodplain flow can be modelled by using spill (Equation 3.2) (Flood modeller, 2017).

Equation 3.2 The spill coefficient equation

$$C_d = \frac{d^{0.67}\sqrt{(1 - m)}}{n\sqrt{DX}}$$

Where in Equation 3.2; d is average depth of flow (m); DX is the distance between spill source and sink (m); n is Manning's n for the region of flow (eg 0.1); m is the user defined modular limit (eg 0.8) (Flood modeller, 2017).

3. Drowned Weir Flow

When the Floodplain Section is connected between two Reservoirs, Drowned Weir Flow equation is used (Flood modeller, 2017).

Equation 3.3 Drowned Weir Flow equation

$$q_s = \frac{C_b b y_1\sqrt{(y_1 - y_2)}}{\sqrt{(1 - m)}}$$

Where in Equation 3.3: y_1 is water depth above section in upstream cell; y_2 is water depth above section in downstream cell; m is modular limit; b is width of segment (Flood modeller, 2017).

4. The US BPR Bridge

The modelling of a bridge structure in Flood Modeller Suite could be performed by using the bridge structure unit (Flood modeller, 2017). A sample of the bridge in the model can be found in Figure 3.5. The US BPR Bridge can be used to compute the afflux at bridges using the methodology developed by the US Bureau of Public Roads (US BPR). The bridge afflux is calculated by using the methods described in Hydraulics of Bridge Waterways (1978) (Flood modeller, 2017).

Figure 3.5 Road bridge (Atkins, 2004)

To set up the bridge section into the model, a River section can be required at the upstream of the US BPR Bridge and this point is the maximum backwater. In addition, a River section can be required at the downstream of the US BPR Bridge and this point has the normal water level (Flood modeller, 2017).

Equation 3.4 The expression for computation of backwater upstream from a bridge constricting flow

$$h_1^* = K^* \alpha_2 \frac{V_B^2}{2g} + \alpha_1 \left[\left(\left(\frac{A_B}{A_4}\right)^2 - \left(\frac{A_B}{A_1}\right)^2\right)\right] \frac{V_B^2}{2g}$$

Where in Equation 3.4: h_1^* is total backwater (or afflux); $K^*$is total backwater coefficient; a_1 is kinetic energy coefficient at the upstream section; a_2 is kinetic energy coefficient in the constriction; V_B is average velocity in constriction; A_B is gross water area in constriction; A_4 is water area in downstream section; A_1 is total water area in upstream section including that produced by the backwater (Flood modeller, 2017).

5. Reservoir

There is Farnley flood storage reservoir in the model.

Equation 3.5 The conservation of mass equation

$$q_{net} - A(h) * \frac{\partial h}{\partial t} = 0$$

$$q_{net} = \sum_{1}^{N} q_i$$

Where in Equation 3.5: h is water surface elevation, ∂t is time step; N is number of inflows; q_i is flow at node; A is surface area of the reservoir (Flood modeller, 2017)

6. The Rectangular Conduit

A 4-kilometre culvert was modelled on the Lower Wortley Beck area as the Rectangular Conduit. The Rectangular Conduit is based on the Saint-Venant equations, which express the conservation of mass and momentum of the water body. The equations used for the Rectangular Conduit are the mass conservation or continuity equation (Flood modeller, 2017).

The continuity and momentum equation can be expressed as Equations (3.6) and (3.7) (Flood modeller, 2017).

Equation 3.6 Continuity Equation

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

Where in Equation 3.6: q is lateral inflow (m^3/s/m); Q is the flow (m^3/s); A is cross section area of flow (m^2); X is longitudinal channel distance (m); t is time (s)

Equation 3.7 The momentum conservation or dynamic equation

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial X}\left(\frac{\beta Q^2}{A}\right) + gA\frac{\partial h}{\partial x} - g\frac{AQ/Q/}{k^2} = 0$$

Where in Equation 3.7: t is the time (s); β is the momentum correction coefficient; g is the gravitational acceleration (m/s^2); h is the water surface elevation above datum (m) and k is channel conveyance (Flood modeller, 2017).

Equation 3.8 Channel conveyance (k)

$$k^2 = A^2 \frac{R^{4/3}}{n^2}$$

Where in Equation 3.8: n is Manning's roughness coefficient; R is hydraulic radius = (A/P) (Flood modeller, 2017)

The relationship between stage (water level) and discharge is normally estimated by using Manning’s equation.

The representation of some of the hydraulic structures was simplified in order to improve the stability of model runs.

3.2.3 2D Free Surface Shallow Water Flow Equations

TUFLOW “Classic” (Two-dimensional Unsteady FLOW) is a two-dimensional depth-averaged hydrodynamic model. It can model free surface flow pattern of the catchment. TUFLOW software uses the Finite Difference Alternating Direction Implicit (ADI) solution scheme to solve the full Two-dimensional (2D) free surface Shallow Water flow Equation (SWE). This 2D SWE solution scheme was proposed in Stelling (1984). The Stelling`s (1984) scheme is an alternating direction implicit finite difference based on the well-established Leendertse`s (1967, 1970) schemes (Syme, 1992). The 2D SWE consist of continuity and conservation of momentum equations in the horizontal x and y directions in Cartesian coordinates (Syme 1992; Krupka, et al., 2007; BMT WMB, 2010; Abdullah 2012).

The 2D Continuity equation

Equation 3.9 The 2D Continuity

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (Hu)}{\partial x} + \frac{\partial (Hv)}{\partial y} = 0$$

Equation 3.10 X Momentum

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - c_f\, v + g\frac{\partial \zeta}{\partial x} +$$
$$g\,u\left(\frac{n^2}{H^{4/3}} + \frac{f_l}{2g\Delta g}\right)\sqrt{u^2+v^2} - \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \frac{1}{\rho}\frac{\partial p}{\partial x} = F_x$$

Equation 3.11 Y Momentum

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + c_f\, u + g\frac{\partial \zeta}{\partial y} +$$
$$g\,v\left(\frac{n^2}{H^{4/3}} + \frac{f_l}{2g\Delta g}\right)\sqrt{u^2+v^2} - \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \frac{1}{\rho}\frac{\partial p}{\partial y} = F_y$$

Where in Equation 3.9, 3.10 and 3.11: ζ is water surface elevation; u and v are depth averaged velocity components in X and Y directions; H is depth of water; t is Time; x and y is distance in X and Y directions; Δx and Δy are cell Dimensions in X and Y directions; C_f is Coriolis force coefficient; n is Manning`s n; f_i is Form (Energy) Loss coefficient; p is Atmospheric pressure; ρ is density of water; F_x and Fy is sum of components of external forces (eg.the wind) in X and Y directions (BMT WMB, 2010).

In TUFLOW, the solutions of these equations proceed in stages: Stage 1 has two steps; Step 1 involves solving the momentum equation in the y-direction for the v-velocities. The equation is solved using a predictor/corrector method, which involves two sweeps. For the first sweep, the calculation proceeds column by column in the y-direction. If the signs of all velocities in the x-direction are the same the second sweep is not necessary, otherwise the calculation is repeated sweeping in the opposite direction (BMT WMB, 2010).

The second step of Stage 1 solves for the water levels and x-direction velocities by solving the equations of mass continuity and of momentum in the x-direction. A tridiagonal equation is obtained by substituting the momentum equation into the mass equation and eliminating the x-velocity.

The water levels are calculated and back substituted into the momentum equation to calculate the x-velocities. Stage 2 proceeds in a similar manner to Stage 1 with the first step using the X-direction momentum equation and the second step using the mass equation and the Y-direction momentum equation (BMT WMB, 2010).

3.2.4 Estimation of the inflow hydrographs

After set–up the 1D/2D hydrodynamic model, inflow hydrographs were computed and entered into the model. Inflow hydrograph displayed the discharge from the outflow points of the Farnley Beck (FB) and Farnley Wood Beck (FWB) basins into the Lower Wortley Beck. Inflow hydrograph was estimated by using event-based approach because the catchment did not have sufficient measured flow data. The hydrographs can be computed by using the rainfall-runoff model in the ungauged catchments. Therefore, inflow hydrographs were estimated by using the ReFH rainfall-runoff method. This model was applied by using revitalised boundary unit of the Flood Modeller Suite tool in this research.

The Revitalised Flood Hydrograph (ReFH) FSR/FEH method was generated by the Centre for Ecology and Hydrology. This method has been used since 2006 for the UK catchments. This flood estimation method can be applied to catchments that are bigger than 0.5 km^2. This method consists of three main processes. These are Loss model (Cmax), Routing model (Tp) and Baseflow model (Kjeldsen et al., 2005).

The loss model is used to estimate the net rainfall from total rainfall. Then, the direct runoff is entered into the routing model. Lastly, the Baseflow is added and total discharge into the river channel can be obtained (Kjeldsen et al., 2005).

1. The Critical Storm Duration

To design the fluvial flood events, storm durations (D) for FB and FWB basins were calculated from the response time of the catchment (time to peak, Tp) and the general wetness of the catchment (the standard average annual rainfall, SAAR) from Equation 3.12

Equation 3.12 The Critical Storm Duration

$$D = T_P(1 + \frac{SAAR}{1000})$$

Where in Equation 3.12 (Houghton-Carr, 1999): D is the Critical Storm Duration (h)

Secondly, the response time of the catchment (time to peak, Tp) was calculated to calculate the critical storm duration (h).

T_P = Time to Peak (h)

Equation 3.13 Time to Peak

$$Tp = 1.563 * PROPWET^{-1.09} * DPLBAR^{0.60} * (1 + URBEXT)^{-3.34} * DPSBAR^{-0.28}$$

Where in Equation 3.13 (Kjeldsen, 2007): DPLBAR is mean drainage path length (km); DPSBAR is mean of all the inter-nodal slopes for the catchment (m/km); PROPWET is index of proportion of time that soils are wet; SAAR is Standard Period Average Annual Rainfall (mm); SPRHOST is Standard Percentage Runoff (%) derived using HOST classification; $URBEXT_{1990}$ is a FEH index of urban and suburban land cover in 1990 (Houghton-Carr, 1999; Kjeldsen, 2007).

Storm duration for critical flood peak was produced by using catchment descriptors.

1.1 Catchment descriptors

The catchment descriptors were obtained from the FEH CD-ROM 3.0 (CEH, 2009) by using Easting-Northing coordinates (Table 3.2).

Table 3.2 Catchment descriptors of FB and FWB basins

Catchment Characteristics	FB	FWB
Easting-Northing	424500, 433600	427700, 431400
Area (km^2)	29.67	20.95
$URBEXT_{1990}$	0.1704	0.2314
SAAR	799	731
PROPWET	0.33	0.32
DPLBAR	5.85	4.87
BFIHOST	0.449	0.359
DPSBAR	75.3	61.7

2. Baseflow model

The Baseflow was added as subsurface flow to calculate the total flow of the catchment. This Baseflow can display the outflow from the storage in the basin. The Baseflow was calculated by using Baseflow lag (BL (hours)) Equation 3.14, baseflow recharge (BR) Equation 3.15 and Initial Baseflow (BF_0, (m^3/s)) Equation 3.16. These three Baseflow parameters were computed from catchment descriptors (Kjeldsen et al., 2005) by using Revitalised boundary of the Flood Modeller Suite software.

Equation 3.14 Baseflow Lag

$$\mathrm{BL} = 25.5\,\mathrm{BFIHOST}^{0.47}\ \mathrm{PROPWET}^{-0.53}\ (1 + \mathrm{URBEXT})^{-3.01}\ \mathrm{DPLBAR}^{0.21}$$

Equation 3.15 Baseflow Recharge

$$\mathrm{BR} = 3.75\,\mathrm{BFIHOST}^{1.08}\,\mathrm{PROPWET}^{0.36}$$

Equation 3.16 Baseflow Recharge

$$\mathrm{BF_0, summer} = \mathrm{AREA}\,(33.94\,(\mathrm{C_{ini}} - 85.42) + 3.14\,\mathrm{SAAR}) \times 10^{-5}$$

Where in Equation 3.14, 3.15, and 3.16 (Kjeldsen, 2007): BFIHOST is Baseflow Index derived by using the UK Hydrology of Soil Types (HOST) classification; C_{ini} is initial loss; AREA is Catchment Area (km^2)

3.2.5 Assessment of the land use change and fluvial flood risk

The components of the water balance can be influenced by land-use change (Piao et al., 2007; Kumar et al., 2017). The urbanisation of the sub-catchments could have a significant impact on the fluvial flood risk. Kumar (2017) found that annual surface runoff rose evidently due to the expansion in urbanisation over the years. This situation can be observed at sub-catchment level as well. The impact on the water balance of the sub-catchment can be determined like that infiltration decreases and surface runoff increases (Kumar et al., 2017). This could result in increased river discharge worldwide (Piao et al. 2007). Kumar et al. (2017) stated that the variety and concentration of vegetation land cover could be one of the important parameters to affect the surface runoff and evapotranspiration. WMO and GWP (2008) added that soil, vegetation cover, and land use have a direct impact on the amount of runoff generated. The water balance can be managed by using some land-use management practices and sustainable drainage systems (Kumar et al., 2017). Putro (2013) investigated the impact of urbanisation on the river system and water quality by analysing the rainfall and Urban Extent (URBEXT) values with the changes in the river flow, river temperature, and dissolved oxygen.

As considered the above knowledge, the impact of surface runoff of a sub-catchment on the discharge hydrograph at the outfall of the sub-catchment could be observed. In addition, the relationship between the land use change of a sub-catchment and fluvial flood risk of the downstream location can be investigated.

A part of this research focused to investigate the effects of land use change on the fluvial flood risk. The impact of the land use change was assessed by changing the ratio of the impermeable surfaces thus, surface runoff can be observed. This link was obtained by using urban extent (URBEXT) catchment parameter and 1D/2D hydrodynamic fluvial model in this research. The URBEXT parameter was used to manage the ratio of the impermeable surface in a catchment.

Inflow hydrographs were estimated for different URBEXT values. Firstly, the URBEXT value was increased to assess the impact of the urbanisation. The 1990-year and the 2016-year of URBEXT values were used. Secondly, the URBEXT value was decreased to assess the impact of the Sustainable Urban Drainage Systems (SUDS). Thus, the change of the impermeable surface of the sub-catchment on the discharge hydrograph at the outfall of the sub-catchment could be examined in this research.

Consequently, the impact of the ratio of the impervious surface of sub-catchments (Farnley Beck and Farnley Wood Beck basins) on the flood risk of the downstream area (between The Ring Road and the Gelderd Road, and M621 in Figure 3.16) was assessed.

A. Urbanisation of the sub-catchment and fluvial flood risk

Urban extent is calculated for the 2016 year for two sub-catchments so the impact of future urbanisation on the fluvial flood risk could be assessed by using the Equation 6.8 on Page 53 in FEH VOL 5 (Bayliss, 1999).

Equation 3.17 Urbanisation expansion factor (UEF)

$$UEF= 0.8165+ 0.2254\ TAN^{-1} \{(YEAR-1967.5) /21.25\}$$

$URBEXT_{1990}$ values (obtained from the FEH CD-ROM) were adjusted, by using the Urbanisation Expansion Factor (UEF) according to the year of 2016.

The urban extent of the Farnley Beck (FB) sub-catchment was calculated by using the Equation 3.17, as 0.275 and urban extent of the Farnley Wood Beck (FWB) sub-catchment was calculated as 0.375 for the year of 2016.

B. Reducing the ratio of impermeable surface of the sub-catchment

In this section of the research, the relationship between the ratio of the impermeable surface and discharge at the outfall of the sub-catchment was assessed by decreasing the ratio of the impermeable surface in the sub-catchment. This part can be used to analyse the impact of the sustainable urban drainage systems on the fluvial flood risk.

If sustainable urban drainage systems are applied to the impermeable surfaces, surface runoff could be decreased and slower.

This scenario was applied to the Farnley Wood Beck basin. The rate of the impermeable surface of the Farnley Wood Beck basin was decreased. The minimum rate of the impermeable surface of the Farnley Wood Beck basin was calculated. An empirical relationship between Urban and URBEXT was calculated from Equation 3.18 (Kjeldsen, 2009).

Equation 3.18 An empirical relationship between Urban and URBEXT

$$\text{Urban} = 2.05\ (\text{URBEXT})$$

The total percentage imperviousness (I) was estimated from the functional relationship between URBEXT and Urban. The assumption is that a typical urban area has at least 30 % impermeable surfaces that could be the minimum total percentage imperviousness in that urban (Kjeldsen, 2009). The total percentage imperviousness is calculated by using Equation 3.19.

Equation 3.19 Total percentage imperviousness

$$I = 30\%\ \text{Urban} = 30\%\ 2.05\ \text{URBEXT} = 0.615\text{URBEXT}$$

The value of $URBEXT_{1990}$ of the FWB sub-catchment is 0.23.

The urban extent value of FWB basin is calculated as 0.15 as having minimum impervious surface by using the Equation 3.19.

C. Calculation the effect of the urbanisation on the inflow hydrographs

Inflow hydrographs were produced from urban part and the sections of Undeveloped (Rural Area) and Paved (Urban Area) of the ReFH framework of the Flood Modeller Suite. To calculate this, impermeable surface and rural area of the sub-catchments were computed by using Equations 3.20 and 3.21.

Equation 3.20 Undeveloped (Rural Area)

Undeveloped area = (AREA - (AREA*URBEXT))

Equation 3.21 Paved (Urban Area)

Paved area = (AREA*URBEXT)

In this study, the developed area was accepted as paved, drawing towards watercourse. Runoff was accepted 70 percent for impermeable surfaces (Flood modeller, 2017).

Table 3.3 Urbanisation of Farnley Beck (FB) basin

URBEXT value	(1990yr) 0.17	(2016yr) 0.275
Undeveloped (km^2)	24.6	21.5
Urban(km^2)	5.0	8.13

Table 3.4 Urbanisation of Farnley Wood Beck (FWB) basin

URBEXT value	(SUDs) 0.15	(1990yr) 0.23	(2016yr) 0.375
Undeveloped (km^2)	17.81	16.10	13.09
Urban (km^2)	3.14	4.85	7.86

According to the above assumptions, Urban (impermeable surface) and Undeveloped (permeable surface) of Farnley Beck (FB) basin (Table 3.3), and Farnley Wood Beck (FWB) basin (Table 3.4) were computed.

3.3 Calibration of the fluvial flood model

The fluvial model of the Lower Wortley Beck was tested for the credibility of the results in this section. The calibration process was the comparison of the measured data of the Pudsey gauge station to the predicted results from the fluvial model of the Lower Wortley Beck.

Measured water level data was taken from Pudsey gauge station and measured rainfall data was taken from Headingley, Knostrop and Heckmondwike gauge stations. These datasets were provided by Environment Agency during this research.

The predicted results from the fluvial model of the Lower Wortley Beck were computed for the same location as the Pudsey gauge station (Figure 3.6).

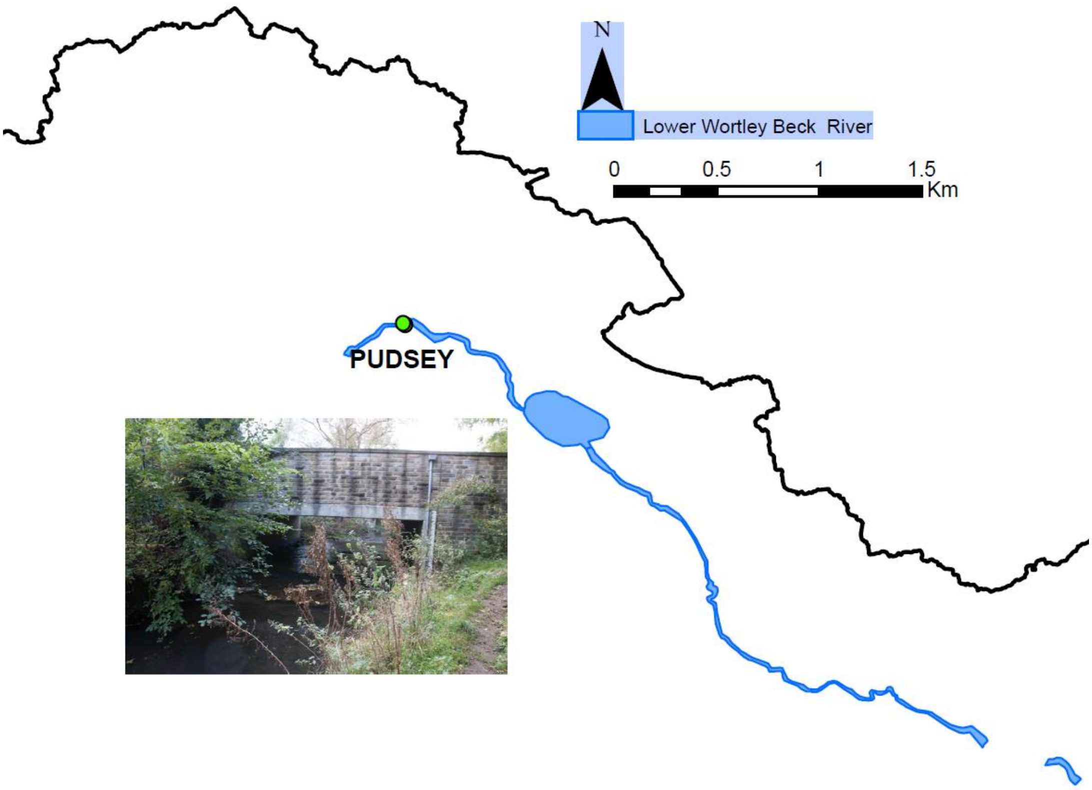

Figure 3.6 The location of Pudsey gauge station

Figure 3.6 displays the location of the Pudsey stage gauge station. This location presents both observation point and computed point.

According to the data quality and historical flood events, the data of 06/07/2012 date and 24/09/2012 date were selected. Measured rainfall data from Headingley, Knostrop and Heckmondwike gauge stations were assessed for these dates and were adjusted by using mean precipitation theory (Thiessen method) for the catchment area. To calibrate the model, firstly, measured rainfall data was entered into the ReFH rainfall-runoff framework tool of the Flood Modeller Suite. Hydrograph was produced for each Farnley Beck and Farnley Wood Beck basins. Inflows from these sub-catchments into the Lower Wortley Beck were computed by using this rainfall data. Next step was to enter these inflow hydrographs into the fluvial model of the Lower Wortley Beck and to compute water depth for the Pudsey Location.

1. **06/07/2012 Event day for calibration**

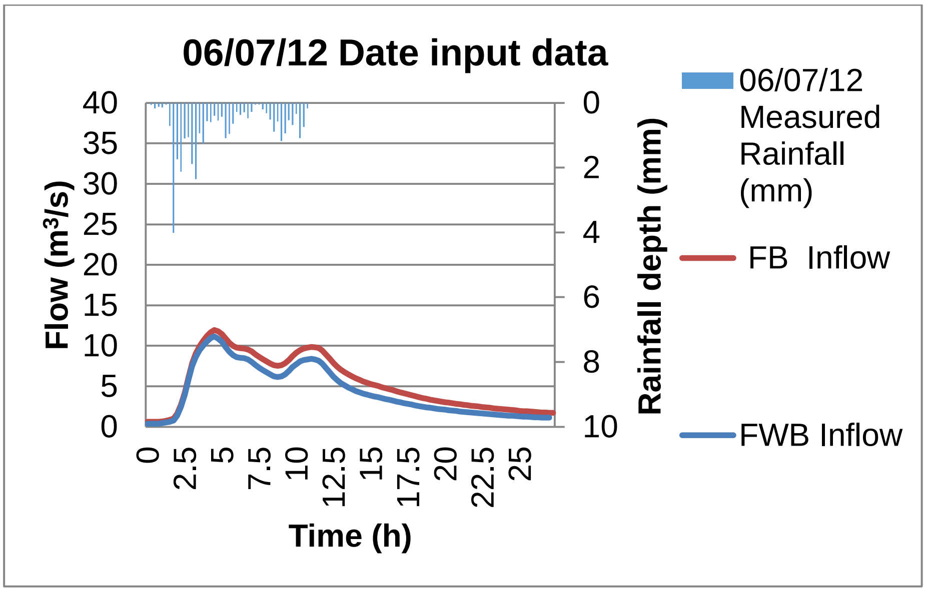

Figure 3.7 06/07/2012 Date input data

Calibration input data of the 06/07/2012 date can be seen in Figure 3.7

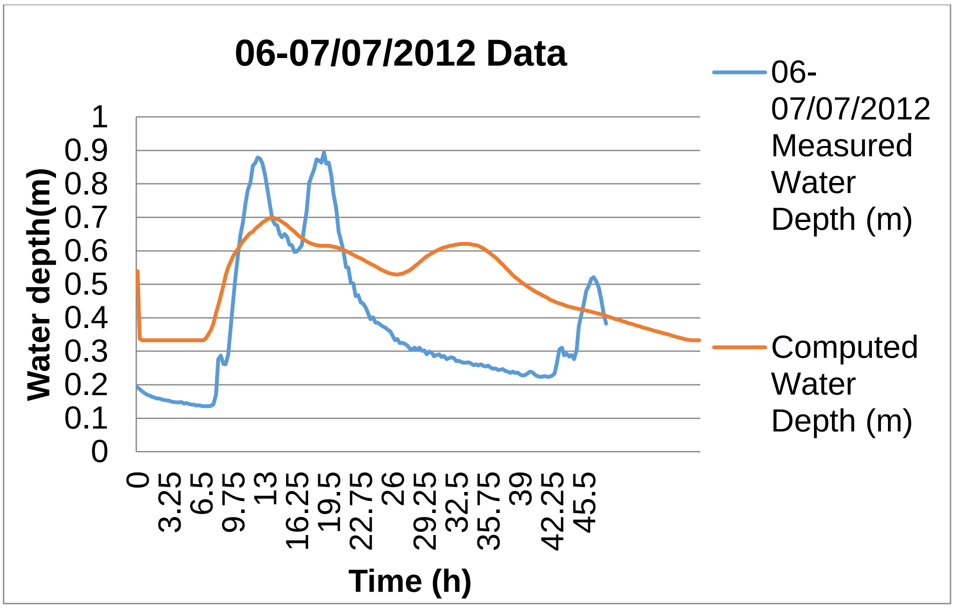

Figure 3.8 Water depth (m) from 06/07/2012 event day

The measured water depth (m) data from observed Pudsey gauge station and the computed water depth (m) data from the Lower Wortley Beck fluvial model were compared for 06/07/2012 event day. Maximum measured water depth is 0.9 m, and maximum computed water depth is 0.7 m (Figure 3.8).

2. 24/09/2012 event day for calibration

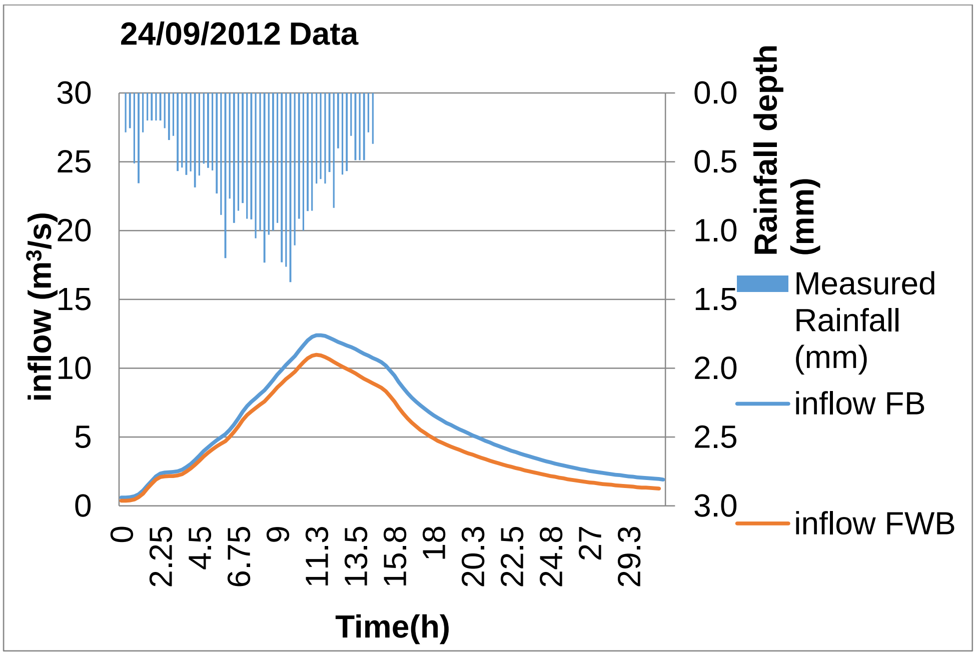

Figure 3.9 Figure 3.9 24/09/2012 Event Date input data

Calibration input data of the 24/09/2012 date can be seen in Figure3.9.

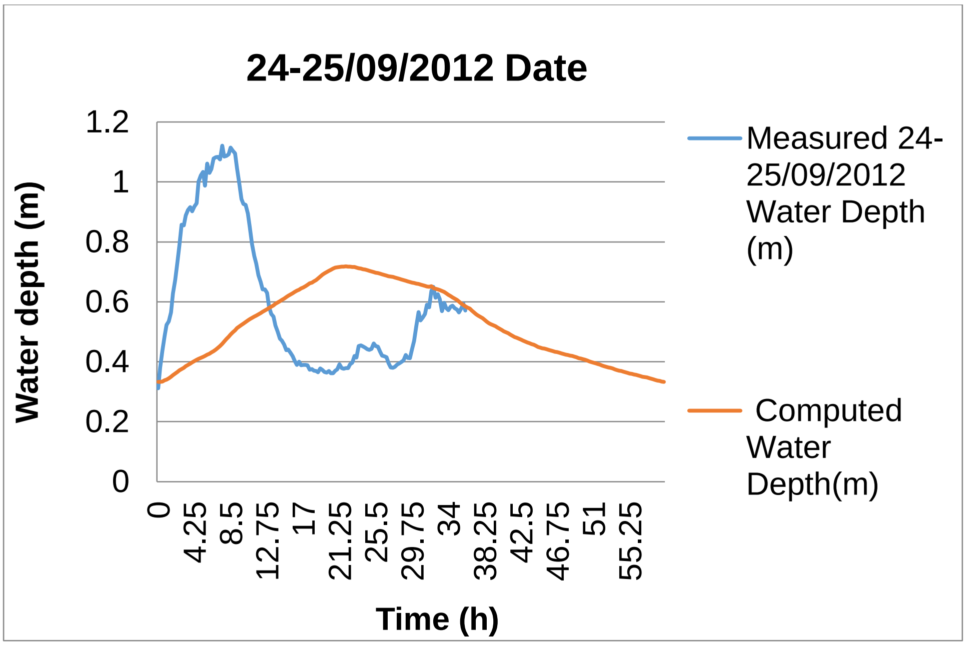

Figure 3.10 Water depth (m) from 24/09/2012 event day

The measured water depth (m) data from observed Pudsey gauge station and the computed water depth (m) data from the Lower Wortley Beck fluvial model were compared for 24/09/2012 event day. Maximum measured water depth is 1.1 m, and maximum computed water depth is 0.7 m (Figure 3.10).

The differences could be because the geomorphology of the river channel could not be displayed exactly in the model.

3.4 Results and Discussions

Catchment response time (time to peak (T_P)) and storm duration (D) of Farnley Beck (FB) and Farnley Wood Beck (FWB) basins were calculated to estimate inflow hydrographs of the Lower Wortley Beck. Ungauged catchment equations of the ReFH rainfall-runoff method (Kjeldsen, 2007) were used.

$URBEXT_{1990}$ values of the FB and FWB basins are 0.17 and 0.23 respectively. Catchment response time of the FB and FWB basins are 2.7 h and 2.2 h respectively. The estimated rainfall duration values of the FB and FWB basins are 4.8 h and 3.8 h respectively. The urban area of FB basin is 5.06 km^2, and FWB basin is 4.8 km^2 in 1990 yr.

$URBEXT_{2016}$ values of the FB and FWB basins are 0.27 and 0.375 respectively. Catchment response time of the FB and FWB basins are 2.0 h and 1.5 h respectively. The estimated rainfall duration values of the FB and FWB basins are 3.6 h and 2.64 h respectively

While the ratio of impervious surface increases (URBEXT values), both time to peak and rainfall duration decrease so that catchment response becomes faster.

The above rainfall duration (h) and time to peak values (h), and the URBEXT values were used to obtain the inflow hydrographs. Inflows from FB and FWB basins into the Lower Wortley Beck were computed. Inflow hydrographs were produced to display the discharge from FB and FWB sub-catchments into the Lower Worley Beck. The results were displayed by producing probabilistic flood inundation maps. The background of Figure 3.12, 3.18, 3.19, 3.23, 3.24, 3.28, 3.30 and 3.32 were produced by using OS 1:25 000 Scale Colour Raster and contain OS data © Crown copyright and database right (2015) (Ordnance Survey, 2015). Arc MAP 10.2.2 tool was used to produce these maps.

3.4.1 Fluvial Flood Risk at the Lower Wortley Beck

The hydrographs were estimated for a 1% annual exceedance probability (AEP) event by using the ReFH rainfall-runoff method. In addition to this, $URBEXT_{1990}$ value was used for FB and FWB basins. Inflow hydrographs were displayed in Figure 3.11.

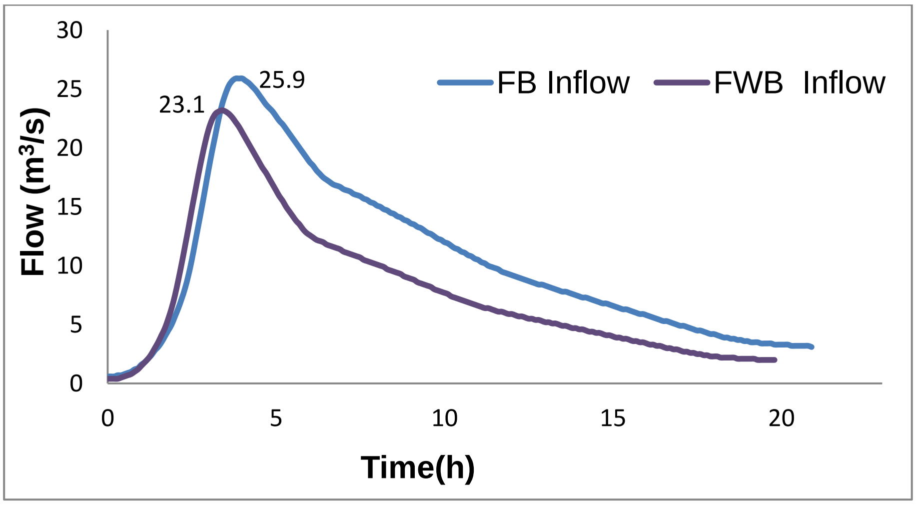

Figure 3.11 Inflow hydrographs

The peak flow of FB basin hydrograph is 26 m^3/s at the 4^{th} hour of simulation (Figure 3.11). Peak flow of FWB basin hydrograph is 23 m^3/s at the 3.4^{th} hour of simulation (Figure 3.11).

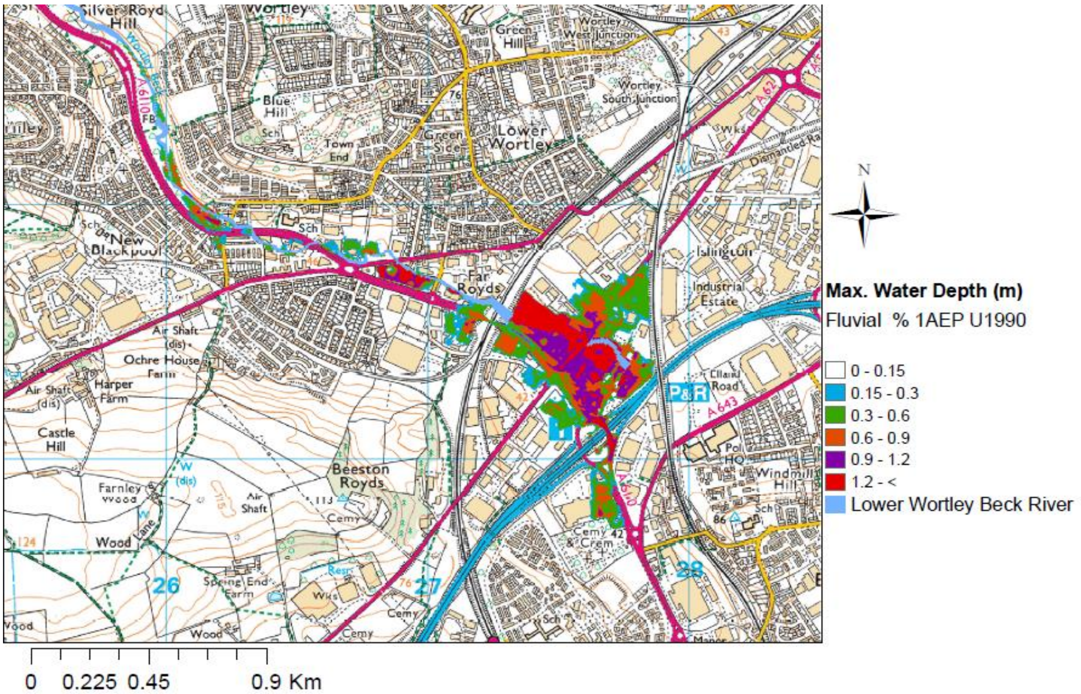

Figure 3.12 Flood inundation map

This above probabilistic flood inundation map was created to display flood extent for the 1 in 100-year event by using the $URBEXT_{1990}$ value of the sub-catchments (Figure 3.12).

This event was analysed in detail in Figure 3.13, Figure 3.14 and Figure 3.15 maps.

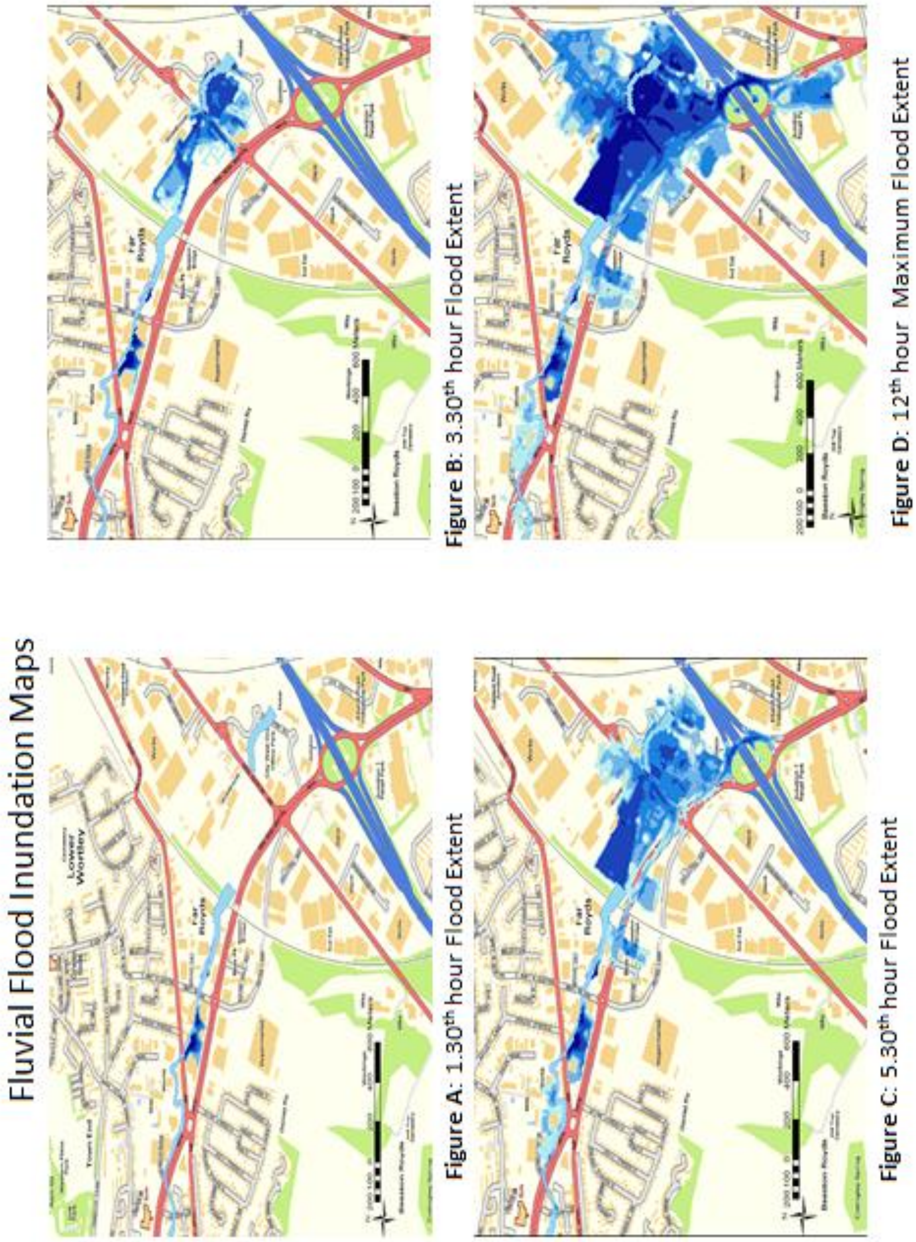

Figure 3.13 ReFH URBEXT$_{1990}$ 1% AEP (flood movements)

Background of Figure 3.13 that is street view contains OS data © Crown copyright and database right (2013) (Ordnance Survey, 2013).

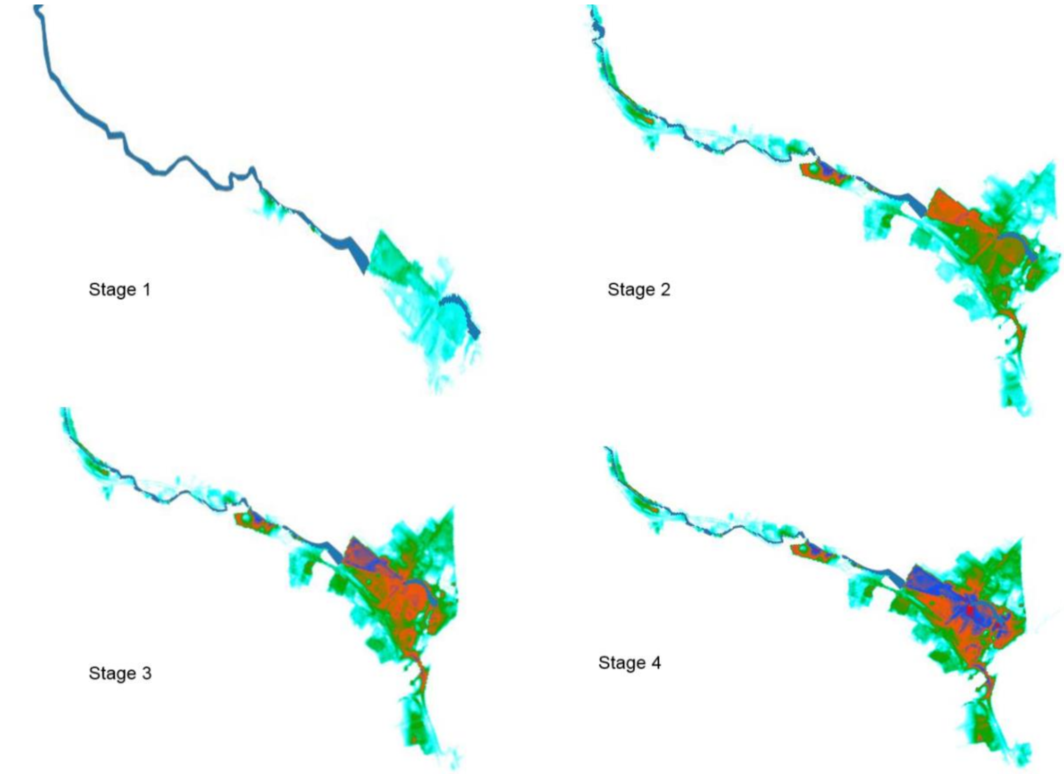

Figure 3.14 Fluvial flooding 1 % AEP (water depth / stages)

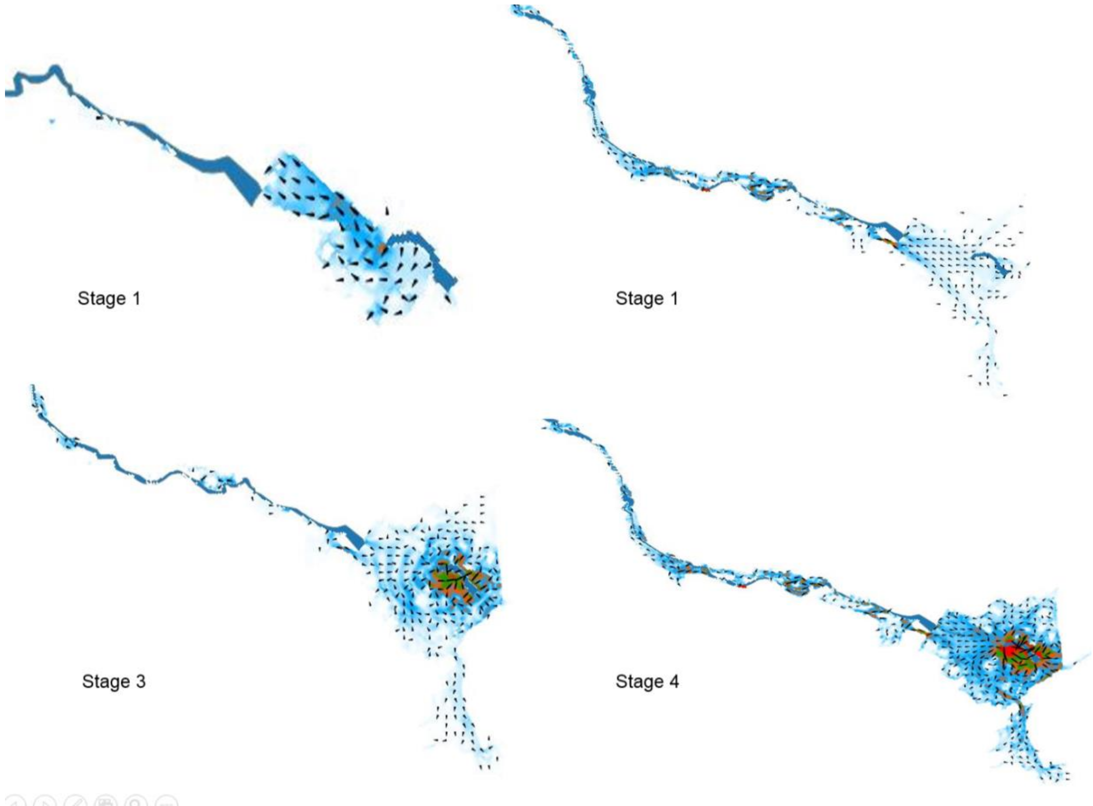

Figure 3.15 Fluvial flooding 1 % AEP (velocity / stages)

Figure 3.13, Figure 3.14, and Figure 3.15 display fluvial flooding at different times (hour) of the simulation. According to fluvial flood inundation maps in Figure 3.15, Lower Wortley Beck area, specifically, the Gelderd Road, Ring road, and A62 road were observed as primary flood risk areas.

Flood event began at between the Ring road and the A58 Road. Later water cumulated at the Lower Wortley Beck area between the A6110 and the M621 on the Gelderd Road. The reason of this flood could be the limitation of the culvert and reservoir capacity, and so backwater effect was observed.

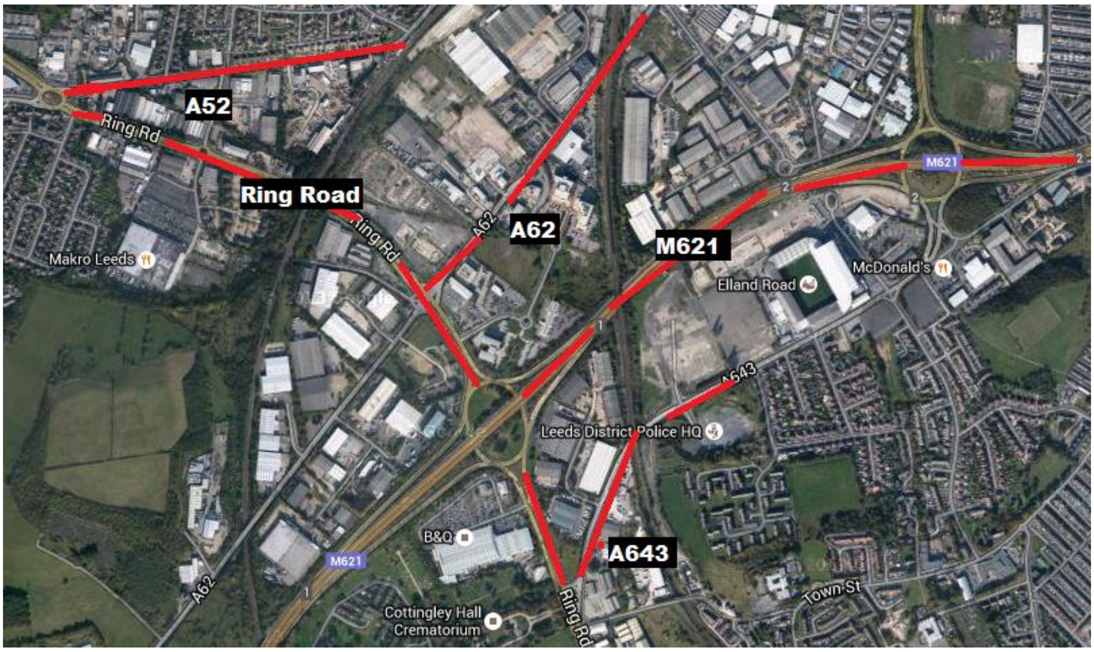

Figure 3.16 Flood risk area

Figure 3.16 presents the map of the Lower Wortley Beck, Leeds, and West Yorkshire (Google Map, 2015). It shows the areas that would be inundated by the flooding of the 1 in 100-year event. The map can be used to identify the built-up locations in the fluvial flood risk. According to the baseline results, primary risk places were determined. It was seen that there are developing places in the fluvial risk location such as industrial and residential settlements. In addition, there is an important transportation link. Consequently, fluvial flood risk should be managed for this area.

3.4.2 The impact of land-use change of sub-catchment on the fluvial flood risk

The impact of Farnley Wood Beck (FWB) basin on fluvial flood risk of the Lower Wortley Beck area was observed.

Below scenarios were created

1. There is no inflow from FWB sub-catchment into the system

2. The impervious surface ratio of FWB basin is 0.375

The impervious surface ratio of FWB basin was changed from 0.23 that is the URBEXT value of the 1990 year, to 0.375 URBEXT value of the 2016 year to assess the future land-use change.

3. The impervious surface ratio of FWB basin is 0.15

The impervious surface ratio of FWB basin is 0.23. It was decreased to the 0.15. The ratio of the impermeable surface was decreased to assess the discharge from FWB.

This assumption can be accepted like that if sustainable urban drainage systems (SUDS) were applied in the Farnley Wood Beck basin, the ratio of the impermeable surface would decrease, and the discharge would be affected.

The limitation of this method that it is an approximate value, also specific flood resilience methods and their locations could not be observed and assessed.

Farnley Beck basin was kept the same as the value of the URBEXT of the 1990 year and the 1 in 50-year event of the inflow hydrograph was used (Figure 3.17).

The inflow hydrographs were estimated for the 1 in 15-year, 1 in 50-year, and 1 in 100-year fluvial flood event for both the baseline and proposed scenarios. To observe this risk, 15-year return period created low flood risk, whereas the 1 in 100-year event created a big flood event and it was an obvious flood risk. Therefore, to observe the influence of Farnley Wood Beck basin on downstream location a 2% AEP flood event was analysed.

The impermeable surfaces of the Farnley Wood Beck basin were computed for each scenario. The ratios of the impermeable surface are 0.15, 0.23, and 0.375 respectively and the area of impermeable surfaces of the FWB basin is 3 km^2, 4.8 km^2, and 7.86 km^2 at each urban percent scenarios.

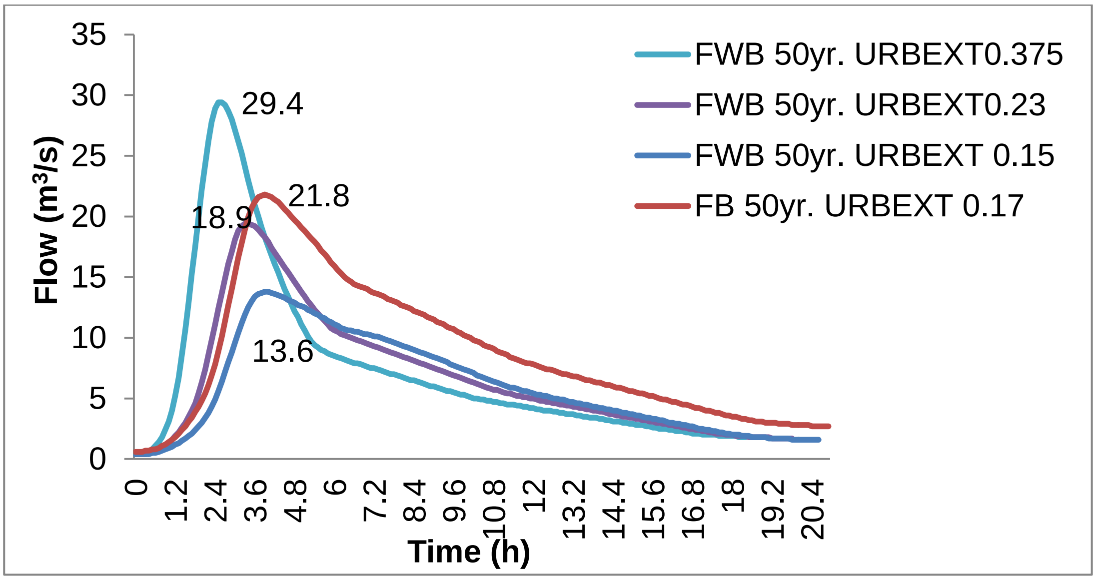

Figure 3.17 Inflows for a 2 % AEP for each URBEXT

Figure 3.17 indicates the inflow values (m^3/s) from the Farnley Wood Beck (FWB) sub-catchment for each URBEXT values. Peak flows of inflow hydrograph from the FWB are 14 m^3/s, 19 m^3/s and 29 m^3/s respectively for a 2 % AEP flood event.

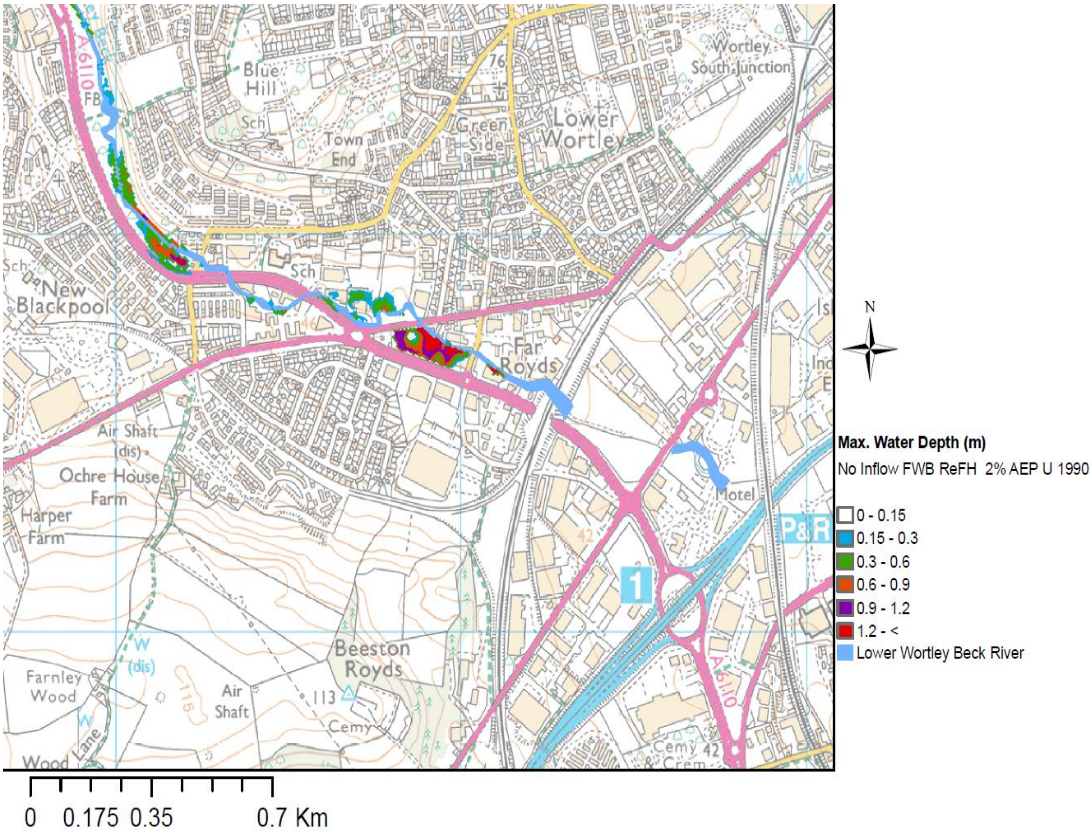

Figure 3.18 Flood extent of no inflow from FWB

Scenario 1 was applied and the flood inundation map in Figure 3.18 was produced.

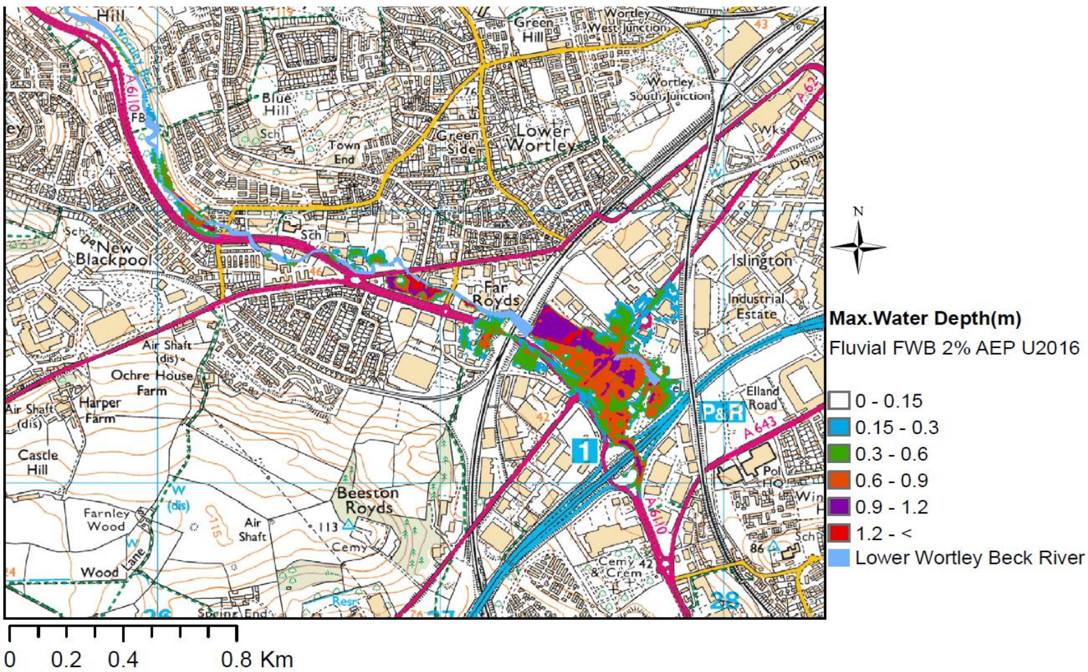

Figure 3.19 Flood extent of inflow from URBEXT$_{2016}$ of FWB

Scenario 2 was applied and the flood inundation map in Figure 3.19 was produced.

It can be observed that there is a significant impact from Farnley Wood sub-catchment on the Lower Wortley Beck fluvial flood risk. In addition, backwater flow movement might be observed at the Lower Wortley Beck area due to the inflow from Farnley Wood Beck, and in consequence of limited culvert capacity. Lastly, Farnley Wood Beck basin has been developing, and urbanisation is expected to be much more in the future.

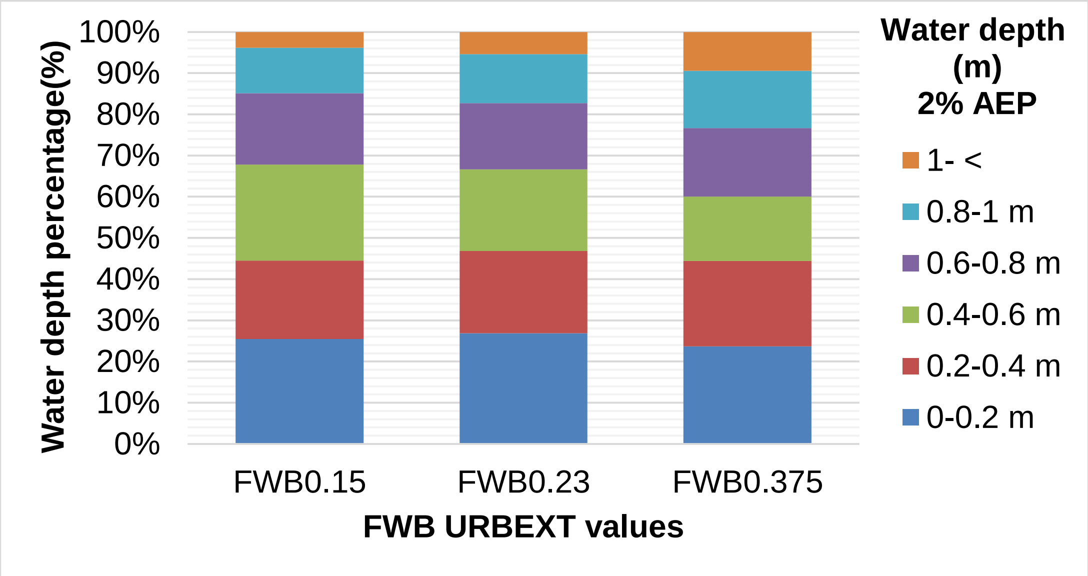

Figure 3.20 Water depth percentage (%)

Figure 3.20 indicates the water depth percentage (%) in the flood inundation area for each scenario of FWB sub-catchment. When the URBEXT value increases, water depth at the flood inundation area can become higher.

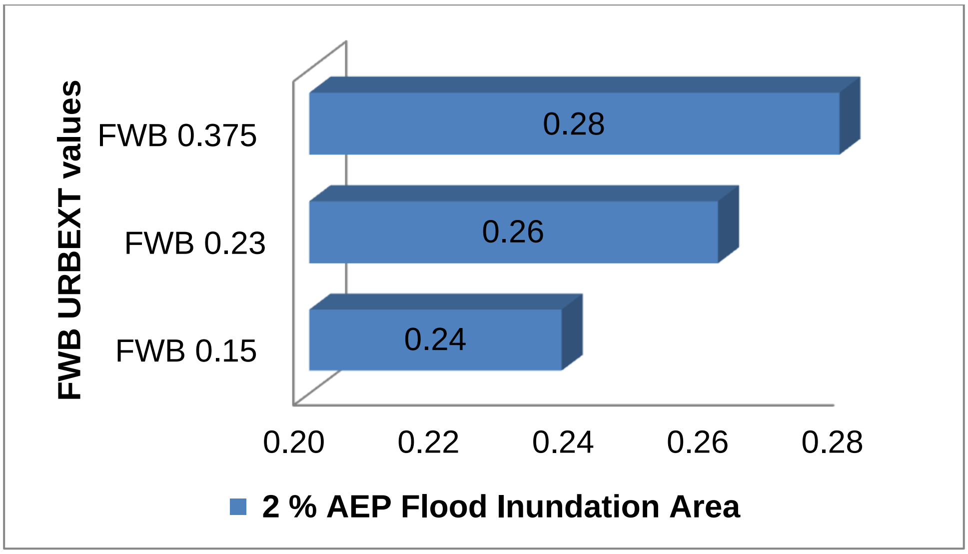

Figure 3.21 Flood inundation area (km^2)

Figure 3.21 indicates the flood inundation area (km^2) for the 1 in 50-year event for each URBEXT values of FWB basin. When the ratio of URBEXT increases, the flood extent area can become greater.

3.4.3 The impact of land use change on the fluvial flood risk

In this section, the impact of the land use change of the sub-catchments on the fluvial flood risk at the Lower Wortley Beck was assessed. Two scenarios were designed.

1. Increasing the ratio of impermeable surfaces of the sub-catchments

The ratio of impervious surfaces was increased so the expected urbanisation in the year of 2016 was calculated.

$URBEXT_{2016}$ values of the FB and FWB basins are 0.27 and 0.375 respectively. The urban area of FWB basin is 4.8 km^2 in 1990 yr. and 7.86 km^2 in 2016 yr. The urban area of FB basin is 5.06 km^2 in 1990 yr., 8.13 km^2 in 2016 yr.

2. A decrease in the ratio of the impermeable surfaces of the sub-catchments

The ratios of impervious surfaces were decreased. After increasing the portion of permeable surfaces of $URBEXT_{1990}$ values of the FWB basin by applying SUDS, the URBEXT value became 0.15; the urban area of FWB basin became 3.14 km^2. Whereas, the SUDS was not applied into the FB basin because its $URBEXT_{1990}$ value is already very small that is 0.17.

These scenarios were applied for the 1 in 100-year event.

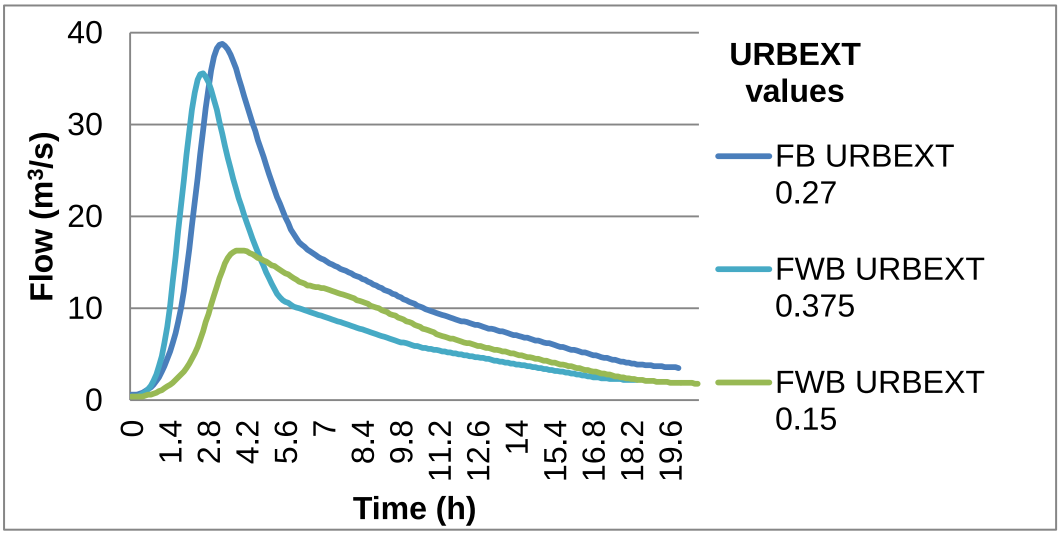

Figure 3.22 Inflow hydrographs of FWB and FB

Figure 3.22 displays the inflows from FWB and FB sub-catchments for the 1 in 100-year event for each URBEXT values. The peak flow of the inflow hydrograph from FB sub-catchment is 39 m^3/s and URBEXT value is 0.27 for the year of 2016 (Figure 3.22). The peak flow of the inflow hydrograph from FWB sub-catchment is 35 m^3/s and URBEXT value is 0.375 for the year of 2016 (Figure 3.22). The peak flow of the inflow hydrograph from FWB sub-catchment is 16 m^3/s and URBEXT value is 0.15 with SUDS (Figure 3.22).

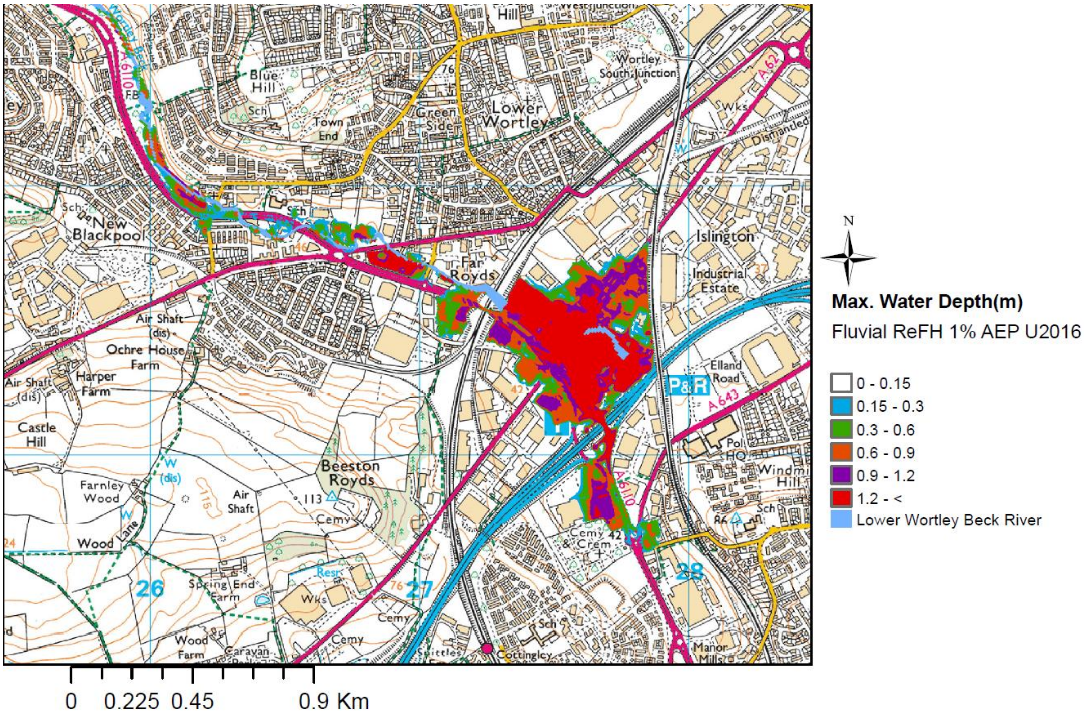

Figure 3.23 Flood extent of inflow from URBEXT$_{2016}$ of FWB and FB sub-catchments

Figure 3.23 indicates the flood extent for the 1 in 100-year event. Inflows hydrographs were estimated for the URBEXT value of FWB basin was 0.375, and URBEXT value of FB basin was 0.27.

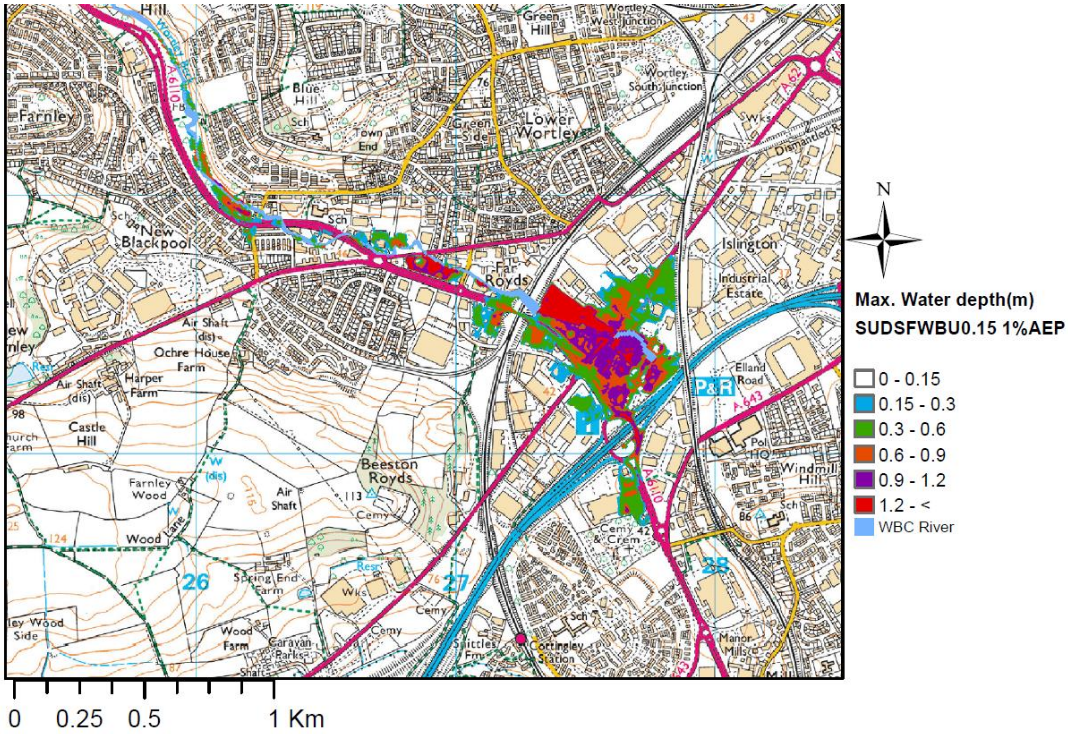

Figure 3.24 Flood extent of inflow from URBEXT value 0.15 FWB and URBEXT value 0.17 FB

Figure 3.24 indicates the flood extent of the 1 in 100-year event. This flood extent is simulated when the value of URBEXT parameter of FWB basin is 0.15 and the value of URBEXT of FB basin is 0.17. In this scenario, there is a decrease in the ratio of impervious surfaces of FWB basin but the ratio of impervious surfaces of FB basin was kept same as in the1990 year.

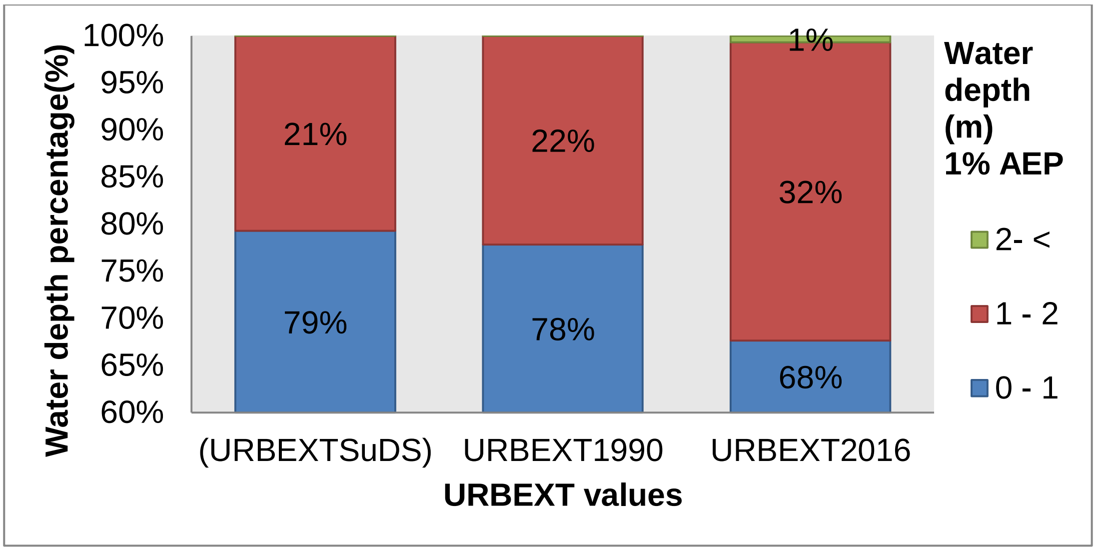

Figure 3.25 Water depth percentage (%)

According to the impact of the land use change of the sub-catchments, maximum water depth (m) was computed. Figure 3.25 indicates maximum water depth percentages of these scenarios. It seems that SuDS did not have a significant impact on the water depth values in the flood extent. It is similar to the scenario of URBEXT $_{1990}$ values. Whereas, urbanisation has a significant impact on the water depth values (m). Water depth became higher in the flood extent.

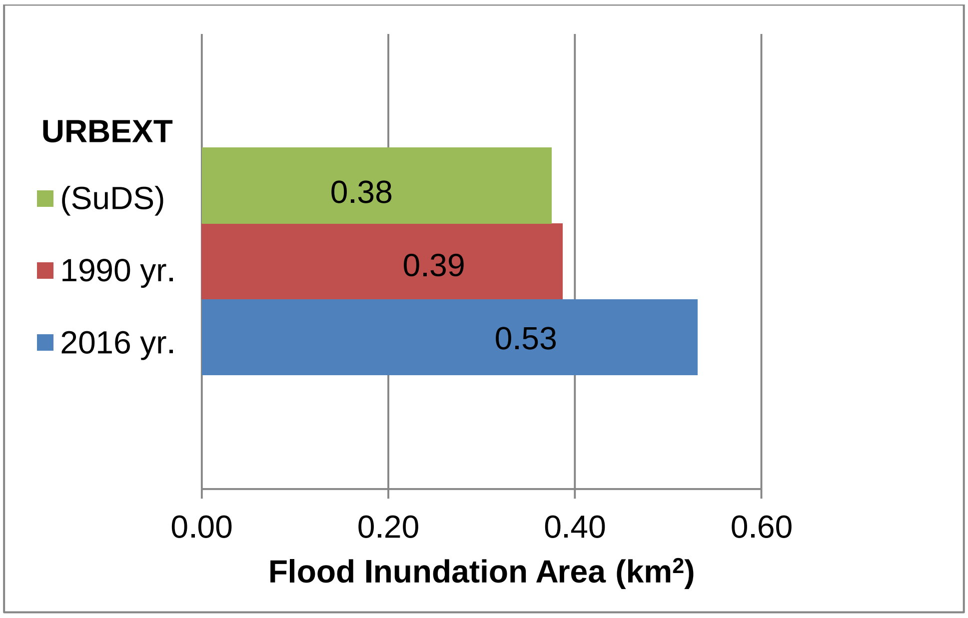

Figure 3.26 Flood Inundation area (km^2)

Flood extent area reached to 0.53 km^2 when urbanisation increased in the catchment (Figure 3.26). However, flood extent area can be decreased to the 0.38 km^2 by applying SUDS.

3.4.4 The impact of rainfall duration on the fluvial flood risk

The impact of the rainfall duration on the inflow hydrograph and downstream fluvial flood risk was investigated in this section. Inflow hydrographs were produced to display the discharge from FB and FWB sub-catchments into the Lower Worley Beck. The hydrographs were estimated for a 1% annual exceedance probability (AEP) event by using the ReFH rainfall-runoff method. In addition to this, URBEXT of the 1990 year was used for FB and FWB basins. The length of the rainfall events in the FB and FWB basins were changed from 0.5 hr. to 1 hr., and then to 6 hr.

1.) Rainfall duration is 0.5 hour in the Wortley Beck catchment

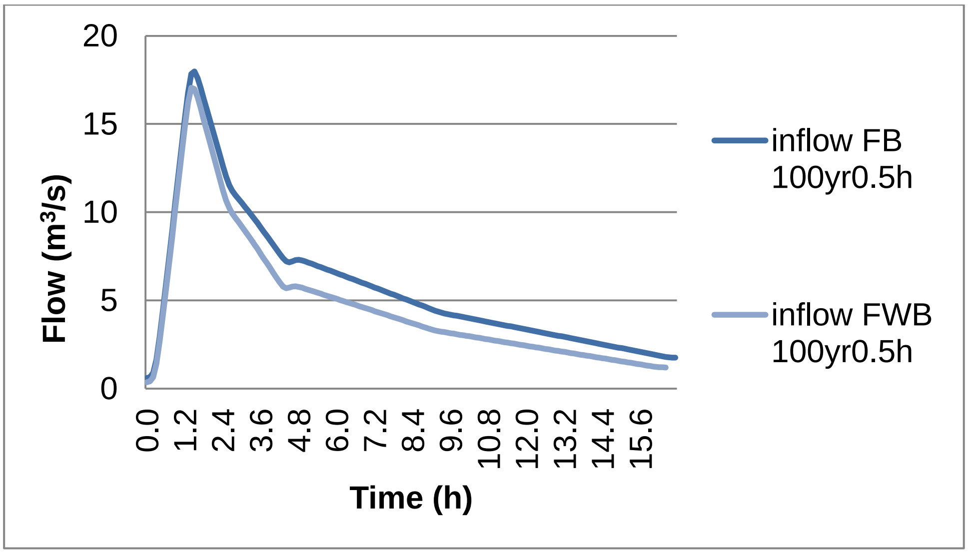

Figure 3.27 Inflow hydrographs for 0.5-hour rainfall duration

Figure 3.27 indicates the inflow hydrographs of the sub-catchments and for 0.5 h rainfall duration for the 1 in 100-year event. The peak flow of inflow hydrograph of FB sub-catchment is 17.9 (m^3/h) and FWB sub-catchment is 17.05 (m^3/h).

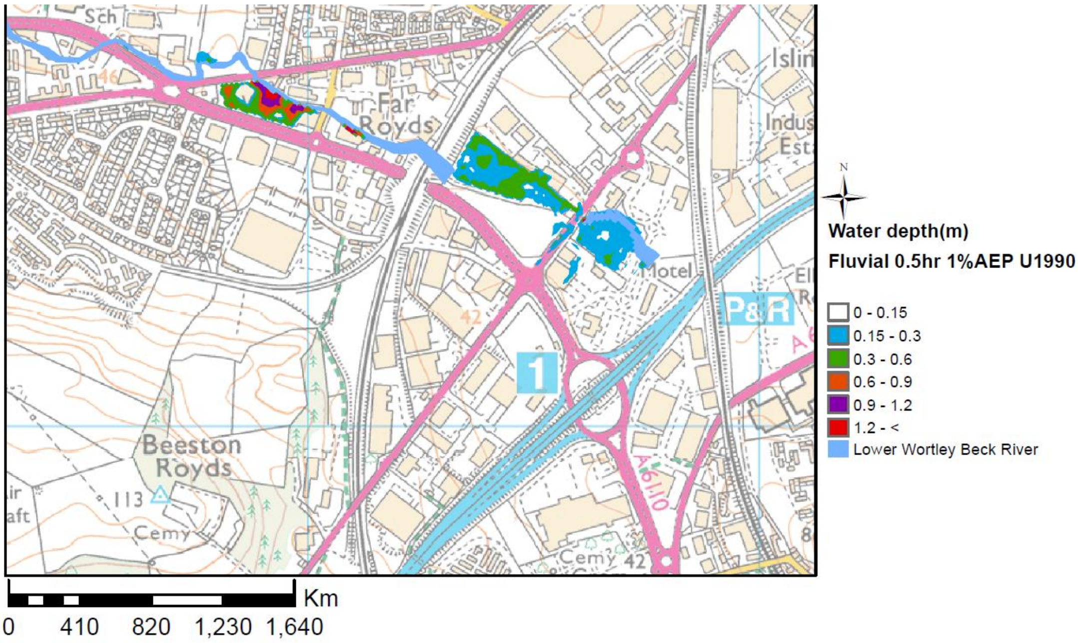

Figure 3.28 Flood extent from 0.5-hour rainfall duration

Fluvial flood inundation area of the 0.5-hour rainfall duration at the Lower Wortley Beck area can be seen in Figure 3.28. Inflow hydrographs were computed for $URBEXT_{1990}$ and for a 1 % AEP. This event does not have a significant flood risk at the Gelderd Road.

2.) Rainfall duration is 1 hour in the Wortley Beck catchment

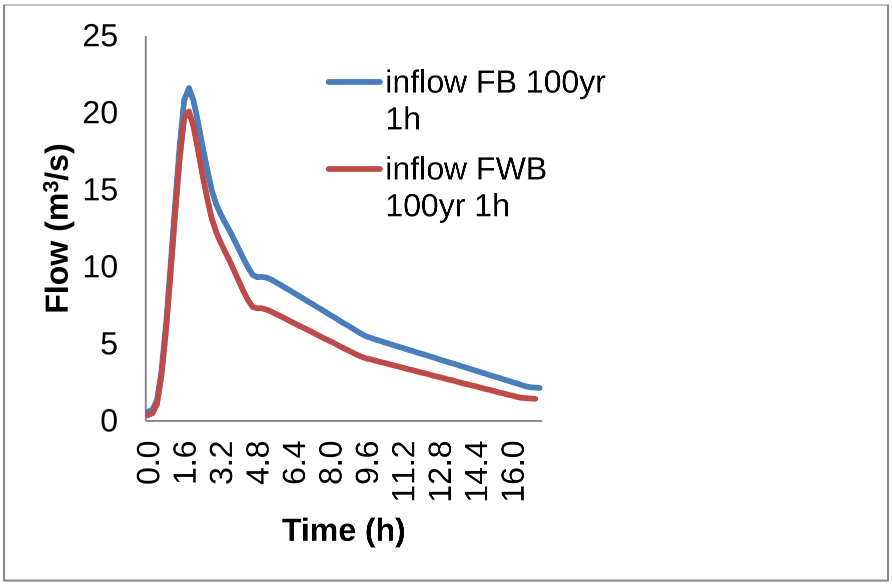

Figure 3.29 Inflow hydrographs for 1-hour rainfall duration

Figure 3.29 indicates the inflow hydrographs of the sub-catchments and for one-hour rainfall duration for the 1 in 100-year event.

Peak flow of inflow hydrograph of FB sub-catchment is 21.6 (m^3/h), and FWB sub-catchment is 20.08 (m^3/h). Fluvial flood inundation area at the Lower Wortley Beck can be seen in Figure 3.30.

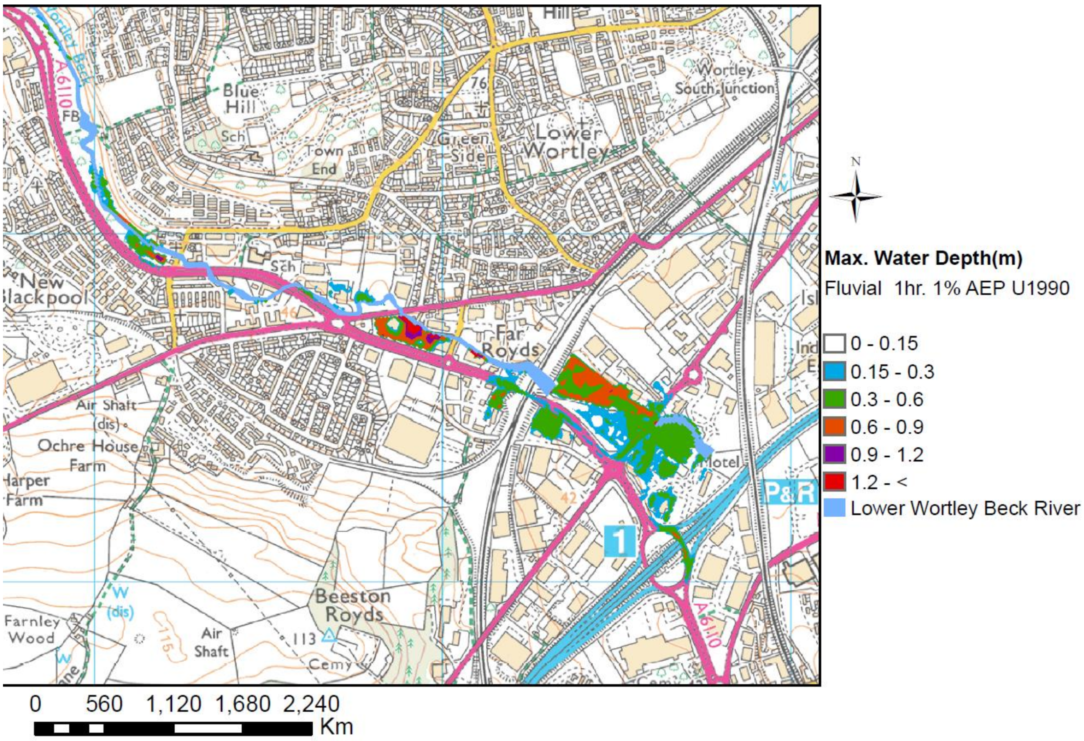

Figure 3.30 Flood extent from 1-hour rainfall duration

Figure 3.30 displays the flood extent from 1-hour rainfall duration and inflow hydrographs were produced from $URBEXT_{1990}$ and for a 1 % AEP flood event.

3.) Rainfall duration is 6hour in the Wortley Beck catchment

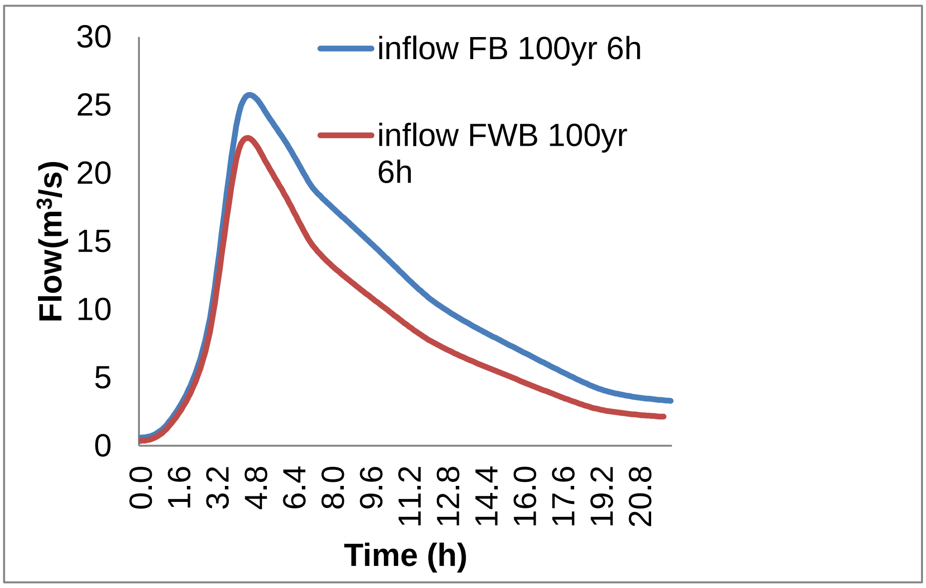

Figure 3.31 Inflow hydrographs for 6-hour rainfall duration

Figure 3.31 indicates the inflows from the sub-catchments, for 6-hour rainfall duration and for the 1 in 100-year event. Peak Inflow value of FB sub-catchment is 25.74 (m^3/h), and Peak inflow value of FWB sub-catchment is 22.59 (m^3/h). Fluvial flood extend at the Lower Wortley Beck area can be seen in Figure 3.32.

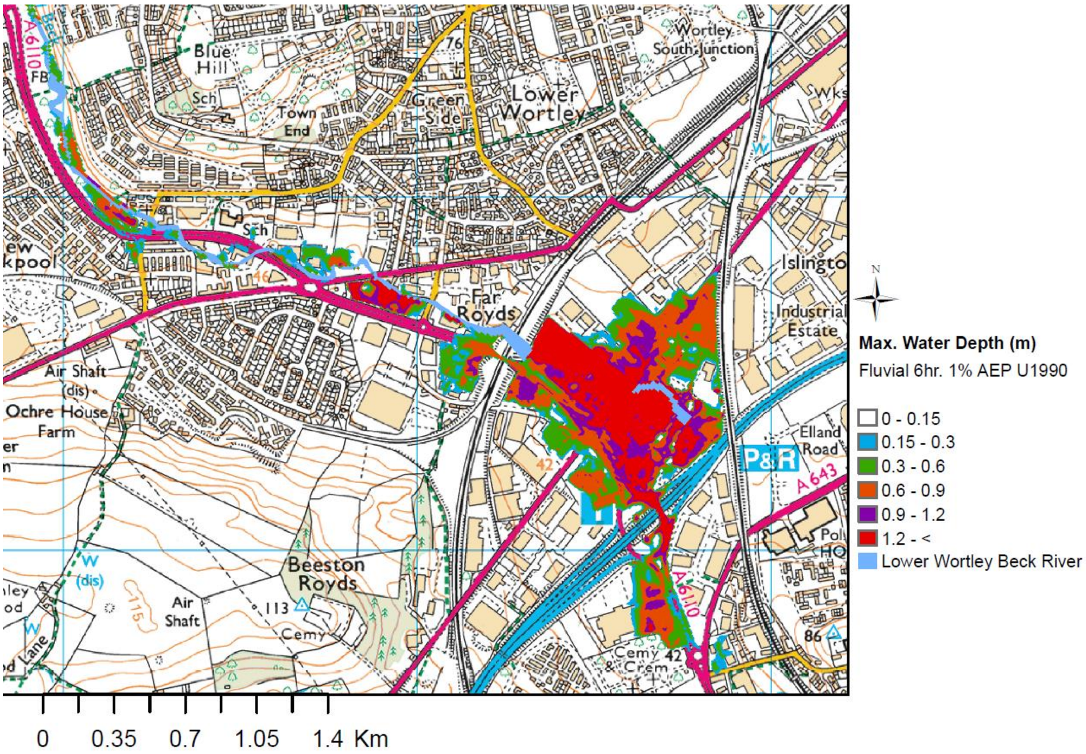

Figure 3.32 Flood extent of 6-hour rainfall duration

Flood inundation area of the rainfall event of the rainfall duration (6-hour) is the biggest one when the rainfall event duration becomes smaller; flood inundation area is also smaller (Figure 3.33). When rainfall duration event is 0.5-hour flood inundation area is 0.07 km^2. When rainfall duration event is 6-hour, flood inundation area is 0.4 km^2.

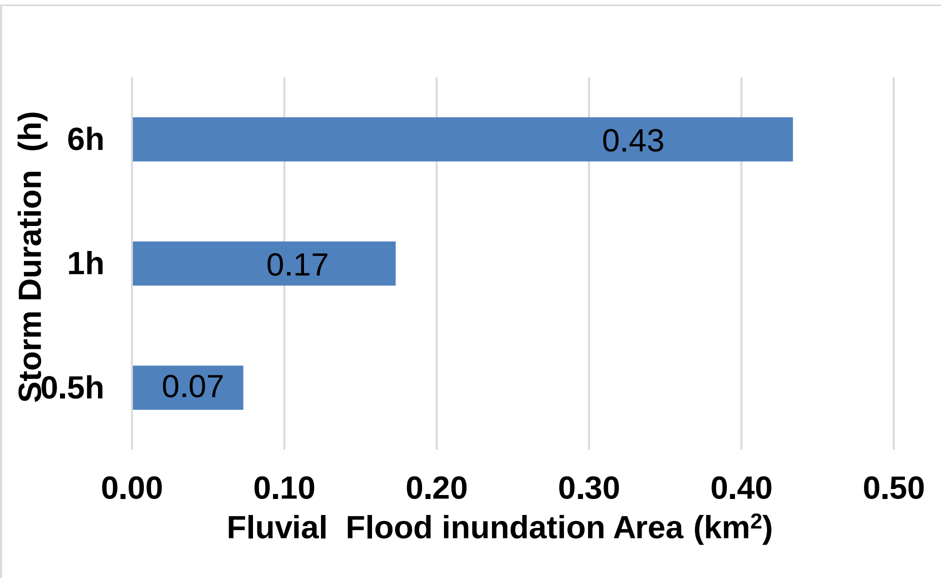

Figure 3.33 Fluvial flood inundation Area (km^2) for each rainfall duration (h) for a 1% AEP

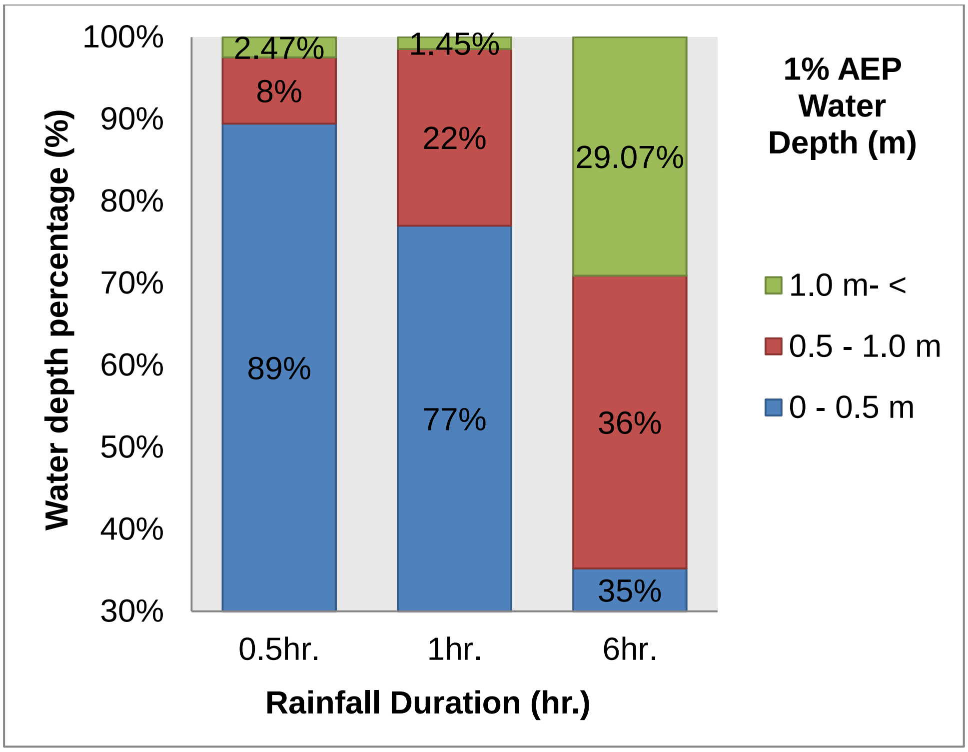

Figure 3.34 Water depth percentage (%) for each rainfall duration (hr.)

Figure 3.34 displays that water depth percentage (%) in the flood inundation area at the Lower Wortley Beck area. The flood inundation area was simulated by using the 1 in 100-year event. Flood event was created by using 0.5 hr., 1 hr., and 6hr., rainfall duration. 6-hour rainfall duration created higher floodwater depth than 1-hour and 0.5-hour rainfall duration. Water depth levels become greater when the rainfall duration become longer in the catchment.

3.5 Conclusion

The fluvial flood event of the Lower Wortley Beck is a sample fluvial flooding from an urban stream. The Lower Wortley Beck area has a severe level of fluvial flood risk and new developments can be found on the floodplains in the area. Therefore, fluvial flood risk can be more series in the future.

The impact of the inflows from sub-catchments of the Wortley Beck catchment on the downstream fluvial flood risk was assessed in this research. The assessment of the Lower Wortley Beck fluvial flood risk insisted in two main sections. These were that the impact of the land-use change of sub-catchments and the impact of rainfall event duration in the sub-catchments.

The land-use change scenarios were used to display the impact of the urbanisation and sustainable urban drainage systems of the sub-catchment on the discharge at the outfall of the sub-catchment. This approach can be useful to have an assumption between the ratio of the impermeable surfaces and its impact on the discharge from the basin.

The impact of the rainfall duration on the downstream fluvial flood risk was assessed as well in this chapter. This approach can be useful to have an assumption between the rainfall event and runoff. Thus, interdependency can be established between surface runoff and discharge in urbanised and ungauged catchments.

The assessment of fluvial flood risk was performed with the probabilistic fluvial flood inundation maps and the maximum water depth (m).

The contributions of this chapter are that

1. The hydrological modelling part of the 1D/2D hydraulic model of Lower Wortley Beck catchment was updated.

Inflow hydrographs were estimated by using the ReFH rainfall-runoff method. Inflows from sub-catchments were produced for different scenarios such as return periods and the critical rainfall duration (h) in this research section.

2. The 1D/2D hydraulic model of Lower Wortley Beck was calibrated.

3. The impact of the ratio of the impermeable surface and the rainfall duration on the fluvial flooding risk were analysed in the Lower Wortley Beck location.

The urbanisation level (URBEXT) of the sub-catchments has a significant impact on the fluvial flood extent and magnitude. When the urbanisation is increased on the sub-catchment, the peak flow can be seen earlier and greater in the hydrograph.

The rainfall event duration becomes shorter, flood inundation area and flood water levels are smaller. Longer rainfall duration can make longer surface runoff thus inflows can become greater.

Chapter 4 Single Event Simulation

4.1 Introduction

This chapter presents an assessment of the impact of the peak discharge on the downstream fluvial flood risk. The peak discharge was used to display the surface runoff of the upstream basin. The assessment was carried by simulating a range of peak flows. The peak discharges were estimated by using the rational method for different rainfall and land-use scenarios. Then, the peak flow was entered into the Flood Modeller Suite-TUFLOW hydrodynamic model to estimate the fluvial flood risk of the Lower Wortley Beck (Figure 4.1).

4.1.1 Research Area

The hydrological analysis of the peak discharge was carried for New Farnley. New Farnley is a small-ungauged urbanised catchment. The catchment boundary of the New Farnley (SE 26150 31850) is shown in Figure 4.1 with the corresponding drainage area of 2.18 km^2. The catchment characteristics were obtained from FEH CD-ROM version 3.0 (CEH, 2009) as shown in Table 4.1 and Table 4.2. Catchment Properties of the New Farnley can be found in Table 4.1.

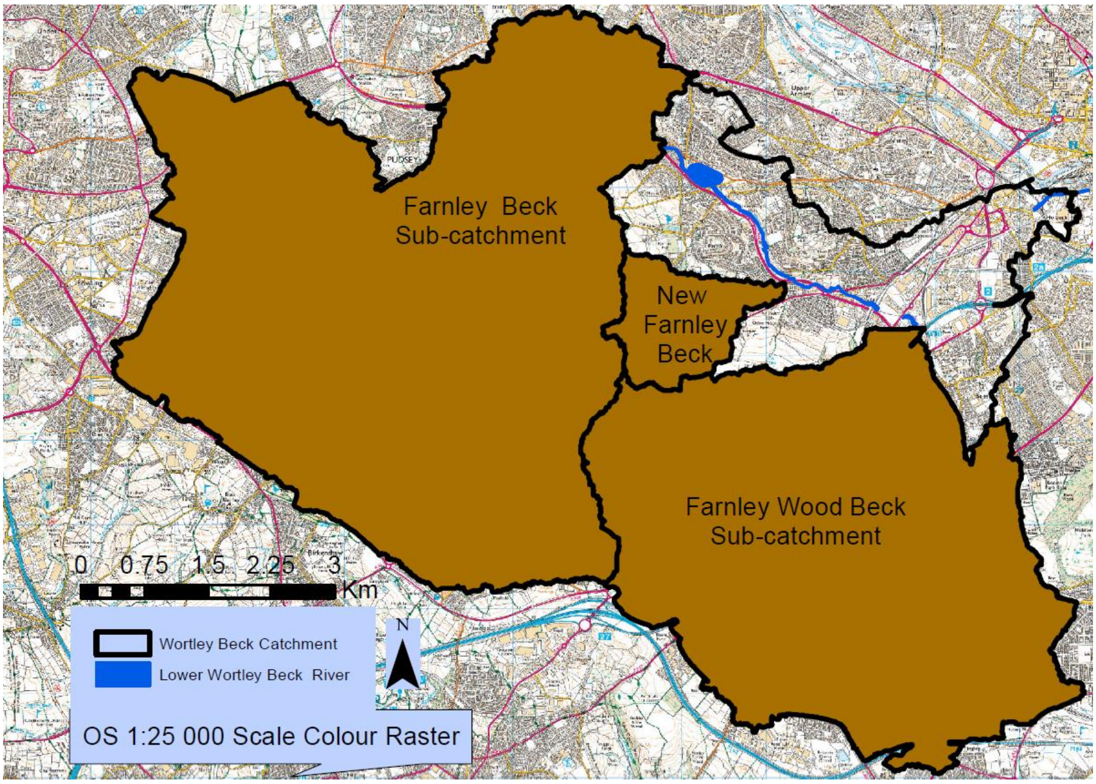

Figure 4.1 Location of New Farnley Beck catchment

Table 4.1New Farnley (Lateral Inflow Sub-Catchment) Properties

DPLBAR	1.41km
DPSBAR	56.5 m/km
PROPWET	0.32
SAAR	742 mm
SPRHOST	38.58
$URBEXT_{1990}$	0.13

Where in Table 4.1: DPLBAR is mean drainage path length (km); DPSBAR is mean of all the inter-nodal slopes for the catchment (m/km); PROPWET is index of proportion of time that soils are wet; SAAR (mm) is Standard Period Average Annual Rainfall (mm); SPRHOST is Standard Percentage Runoff (%) derived by using HOST classification; $URBEXT_{1990}$ is FEH index of fractional urban extent for 1990 (Houghton-Carr, 1999).

Table 4.2 Catchment design rainfall parameters

c	d1	d2	d3	e	f
-0.026	0.377	0.35	0.318	0.301	2.38

The design rainfall parameters of the New Farnley, which were extracted from FEH data CD-ROM version 3.0 (CEH, 2009), are indicated in Table 4.2.

4.2 Research Methodology

The peak flow rates were estimated by incorporating the urban extent (URBEXT) scenarios and the rainfall durations, to analyse the impact of the maximum discharge on the downstream fluvial flood risk. URBEXT value displays the ratio of the impermeable surface in the catchment. In addition, rainfall durations were used to assess the rainfall intensity. Thus, the impact of land-use change and rainfall events on the flood risk could be assessed.

The rational method was selected based on the New Farnley catchment properties. After calculation peak flow by using the rational method, the peak flow was added as lateral flow into the coupled 1D/2D (Flood Modeller Suite link TUFLOW) hydrodynamic model. This modelling approach was the same as Chapter 3 fluvial flood modelling. Fluvial flood modelling consisted of two inflows from Farnley Beck and Farnley Wood Beck basins in the model. In addition to these, the peak discharge at the outfall of New Farnley Beck basin was incorporated as a lateral flow in this methodology. The outcomes of this approach were examined and observed by using the flood inundation maps and water depth values thus the flood risk of the Lower Wortley Beck area was analysed.

4.2.1 The Rational Method

Mulvaney established the principles of the rational method in 1851 (Alsuwaidi et al., 2015). Kuichling (1889) mentioned firstly rational method in the United States (Hayes and Young, 2006). Chow (1964) mentioned that the rational method referred to the Lloyd-Davies approach in England, and was published in 1906. The Rational formula can be used to calculate peak flow in the drainage system in the UK (Chadwick et al., 2004).

Rational method can be used to assess a simplified relationship between rainfall and runoff, and to estimate floods in small and urbanised catchments (Faulkner et al., 2012). In addition, Fleig and Wilson (2013) recommended the rational method in the absence of flood data as an empirical method for small catchments. Watts and Hawke (2003) added that this method has been used for the urban and small rural ungauged catchments (Gebre and Nicholson, 2012). In the UK, the rational method is applied to basins that are between 2 to 4 km^2 size (Gebre and Nicholson, 2012). Whereas, Virginia Department of Transportation recommended the use of the rational method for basins are less than 0.8km^2 in the USA (Hayes and Young, 2006).

The rational method consists of the catchment surface characteristics, average rainfall intensity, and drainage area to calculate the peak flow (Hayes and Young, 2006). Land use change, the ratio of imperviousness, watershed slope, surface roughness, duration and intensity of rainfall, recurrence interval of the precipitation can also have an impact on peak flow (Gebre and Nicholson, 2012; Fleig and Wilson, 2013). For example, if a catchment has low land-surface slopes, or high infiltration rates, and surface storage, it could cause low runoff (Hayes and Young, 2006).

Rational method (Equation 4.1) was used to calculate the peak flow rate for the drainage area.

Equation 4.1Rational method (Houghton-Carr, 1999)

$$\mathrm{Q} = 0.278 \times \mathrm{C} \times \mathrm{i} \times \mathrm{A}$$

Where in Equation 4.1: *Q* is the peak flow rate (m^3/s); i is the rainfall intensity (mm/hr); A is catchment area (km^2); C is the runoff coefficient.

4.2.2 Modified Rational Method

On the other hand, the Institute of Hydrology, Meteorological Office, and HR-Wallingford assessed the rational method and obtained the modified rational method (Gebre and Nicholson, 2012). The modified rational method could be used to design drainage systems (Faulker et al., 2012).

4.2.3 The parameters of the calculation peak flow

The parameters of the equation to calculate peak flow are the runoff coefficient, catchment area (km^2), and the rainfall intensity (mm/hr). These parameters were explained for both the rational method and the modified rational method.

1. The runoff coefficient

Runoff coefficient (C) was used to calculate the peak flow. The runoff coefficient is a dimensionless empirical coefficient (Hayes and Young, 2006). The runoff coefficient can be between 0.1 and 0.5 in the rational method (Houghton-Carr, 1999). In the rational method (Houghton-Carr, 1999), the runoff coefficient value was computed by using the ratio of the impervious surface of the New Farney. It is URBEXT parameter of the catchment descriptors (Table 4.1). It can assist to analyse the impact of urbanisation on the runoff.

Urban extent was calculated for the 2016 year for New Farnley by using the Equation 6.8 on Page 53 in FEH VOL 5 (Bayliss, 1999).

Equation 4.2 Urbanisation Expansion Factor (UEF)

$$\mathrm{UEF} = 0.8165 + 0.2254\mathrm{ATAN}\,\{(\mathrm{YEAR} - 1967.5)/21.25\}$$

Equation 4.2 was used to calculate the rate of impermeable surface in the New Farnley and the results were displayed in Table 4.3.

Table 4.3 URBEXT values of the New Farnley

$URBEXT_{1990}$	0.13
$URBEXT_{2000}$	0.19
$URBEXT_{2016}$	0.22

On the other hand, in the modified rational method, the runoff coefficient (C) value was calculated from Wallingford Procedure volume 1(National Water Council, 1981) as given in Equation 4.3 (Chadwick et al., 2013). Runoff coefficient values are higher in the equation of the modified rational method.

Equation 4.3Runoff coefficient of the modified rational method

$$C = CV \times CR$$

Where in Equation 4.3: CR is 1.3 and CV is PR/100 (Chadwick et al., 2004).

PR is urban the percentage runoff of an urban catchment calculated from Equation 4.4.

Equation 4.4 Urban percentage runoff

$$PR = 0.829 \times PIMP + 25 \times SOIL + 0.078 \times UCWI - 20.7$$

Where in Equation 4.4: Percentage runoff represents the proportion of rainfall, which flows directly contribute to in the river; PIMP is percentage impermeable area to total area (URBEXT value); SOIL is a number depending on soil type (BFIHOST value); UCWI is the urban catchment wetness index (mm) (SAAR value) (Chadwick et al., 2004).

PIMP value is the URBEXT values per each year (Table 4.3), SOIL value is used as BFIHOST value is 0.329, UCWI parameter was used as SAAR. SAAR value is 742 from catchment descriptors data (Table 4.1). In the modified rational method, the runoff coefficient (C) value was 0.6.

Nevertheless, the runoff coefficient should be modified due to the change in soil permeability as precipitation occurs (Gebre and Nicholson, 2012; Faulkner et al., 2012). The runoff coefficient can be affected by soil moisture condition, rainfall event, and land use (El-Hames, 2012). Hayes and Young (2006) mentioned that the runoff coefficient could be between 0 and 1.0. While the value of the runoff coefficient is 0, no surface runoff and is 1, a 100% surface runoff can be observed in the basin. The runoff coefficient in a catchment is associated with the infiltration, storage, and evapotranspiration (Hayes and Young, 2006).

2. Catchment Area

Catchment area (A) was accepted as the whole basin area to calculate the peak flow in the rational method (Houghton-Carr, 1999). Whereas, the catchment area was accepted as equal to the area of the impermeable surface of the basin in the modified rational method, that was 0.3 km^2 for $URBEXT_{1990}$ and 0.5km^2 for $URBEXT_{2016}$ (Chadwick et al., 2004).

Calculation of rainfall intensity for the rational method in an ungauged catchment was explained in this section.

4.2.3.1 Rainfall intensity to calculate peak flow

Peak flow (m^3/s) can be calculated by using the rational method from the use of point precipitation (Chow et al., 1988). One of the links between point precipitation and peak flow is rainfall intensity (i). The rainfall intensity represents total precipitation for each unit of time (Nyman et al., 2002). The rainfall intensity can be calculated by dividing the rainfall depth (mm) to the rainfall duration (hr) for any frequency of the catchment of interest. This calculation can be done by producing rainfall Depth (D)/ Duration (D)/ Frequency (F) curve (Nyman et al., 2002, Chadwick et al., 2004).

The DDF curves can be used to estimate total depth (mm) from the rainfall duration and frequency at any point in the catchment when there is not sufficient measured rainfall data in the catchment (Faulkner, 1999; Fitzgerald, 2007). New Farnley is an ungauged catchment so that a DDF curve was plotted by using FEH data CD-ROM v3.0 software by NERC (CEH, 2009). The curve was plotted by entering defined rainfall duration. The time of concentration of the catchment can be accepted as equal to the storm duration (D) (Hayes and Young, 2006). Time to peak (T_P) formula of the ReFH method was applied to calculate the rainfall duration in this work. Rational method and Depth-Duration-Frequency curve can allow the estimation of the peak flow only for the same defined return period of a rainfall event (Fleig and Wilson, 2013). This assumption causes the return period of the peak flow is the same as the return period of the rainfall intensity (Hayes and Young, 2006).

The rainfall-runoff models need a rainfall depth value to design flood events (Faulkner, 1999). Thus, these flood events can be used to design flood defence in ungauged catchments (Faulkner, 1999).

Rainfall duration of the design rainfall event should be computed to calculate rainfall intensity for a rainfall frequency.

1. Calculation of the Storm Duration

Rainfall duration was supplied to compute rainfall depth from FEH data CD for each return period. Storm duration (D) was calculated (Equation 4.5) by using the time to peak. Time to peak was calculated for various URBEXT values by using the ReFH rainfall-runoff method (Equation 4.6). Finally, rainfall intensity was calculated for each frequency by using depth-duration-frequency model. This calculation method of rainfall depth is used in ungauged catchments.

Equation 4.5 Storm Duration (D)

$$D = T_P(1 + \frac{SAAR}{1000})$$

Where in Equation 4.5: D is Critical Storm Duration (h); T_P is Time to Peak; SAAR is Standard Average Annual Rainfall.

SAAR is 742 mm from FEH data CD-ROM v3.0 (CEH, 2009). It can be seen from Equation 4.5 that time to peak should be known to calculate rainfall duration.

T_P was calculated by using the Revitalised Flood Hydrograph (ReFH) method (Kjeldsen, 2007 page 19. Equation 3.19) as follows:

Tp can be calculated by using Equation 4.6 below

Equation 4.6 Time to peak equation

$$Tp = 1.563 * PROPWET^{-1.09} * DPLBAR^{0.60} * (1 + URBEXT)^{-3.34} * DPSBAR^{-0.28}$$

Parameters of the T_P Equation 4.6 can be found in Table 4.1: New Farnley (Lateral Inflow Sub-Catchment) Properties.

2. Plotting rainfall Depth-Duration-Frequency (DDF) Curve

The rainfall duration (hour) and return period (year) are entered into the FEH CD-ROM software to calculate the rainfall depth (mm). The FEH CD-ROM software was generated by NERC (CEH, 2009) for any catchment in the UK (Faulkner, 1999). Joint Environment Agency/Defra funded the project, researchers from the Met Office, CEH, and the Universities of Salford and Sheffield developed the model of rainfall Depth-Duration-Frequency (DDF) for the UK.

The DDF model can estimate rainfall return periods from 2 years. The model is based on the analysis of annual maxima. Data from 1 hour to 8 days can be derived from rain gauges throughout the UK. The Met Office, the Environment Agency, and SEPA supplied the rain gauge data. The model can fit across the UK on a 1-km grid (CEH, 2009; Stewart et al., 2010).

3. Calculation of the rainfall depth (mm)

After the catchment was defined by the outlet coordinates, the rainfall return period and duration were entered into the FEH CD-ROM software. Rainfall duration was used the same as the time of concentration and the return period of rainfall intensity was accepted the same as the return period of the peak flow. Rainfall has been estimated for a return period on the POT scale, by using the approach of FEH Volume 2, Section 2.4 and by using sliding duration. The biggest total rainfall could be captured during the rainfall event, by using sliding duration. Catchment design rainfall parameters (c, d1, d2, d3, e, and f) can be found in Table 4.2.

An areal reduction factor has been applied to a point rainfall to yield a catchment rainfall (Faulkner, 1999; Fitzgerald, 2007). Areal reduction factor values were obtained from FEH CD-ROM v3.0 (CEH, 2009) for the rainfall DDF curves of the New Farnley area (Table 4.3).

4.3 Single Event Simulation Results

These results present the impact of peak discharge at the outlet of a New Farnley basin on the fluvial flood risk of the Lower Wortley Beck.

A.) Rainfall duration and Time to peak

The impact of rainfall duration on the rainfall-runoff process was analysed. Rainfall duration (hr) was calculated from time to peak value to design the rainfall event in ungauged catchments. Time to peak and rainfall durations were calculated by using ReFH rainfall-runoff model (Equation 4.5 and 4.6).

Table 4.4 Time to peak (T_P), rainfall duration (D)

	URBEXT values	Tp	D	Areal reduction factor
URBEXT$_{(1990)}$	0.13	1.4(hr)	2.45(hr)	0.963
URBEXT$_{(2016)}$	0.22	1.1(hr)	1.94(hr)	0.959

While URBEXT value changes from 0.13 to 0.22, time to peak changes from 1.4 hr., to 1.1 hr., and rainfall duration changes from 2.45 hr., to 1.94 hr., for New Farnley area (Table 4.4). The impact of urbanisation on the estimation of the rainfall duration could be observed in Table 4.4. Time to peak shows the catchment response time to the rainfall event. The increase in the ratio of the impermeable surface can cause a decrease in the catchment respond time.

B.) Rainfall return period and rainfall intensity

The rainfall duration (hr) was used to calculate rainfall intensity (mm/h) for various return periods. After calculating rainfall duration as 2.45 hour for urbanisation value of the 1990 year, rainfall intensity (mm/hr) was computed for each rainfall return periods (T) by using FEH CD-ROM v3.0 (Table 4.5).

Table 4.5 Return period (T) and Rainfall intensity (i)

Return period	Intensity (mm/hr)
15 yr.	12.65
50 yr.	17.67
100 yr.	21.42

Rainfall intensity is getting higher with the increase of the rainfall return period.

C.) The relationship between rainfall duration, and rainfall intensity

Rainfall intensity was assessed for various rainfall durations for the New Farnley area in this section. Rainfall return period was used as the 1 in 100-year event to calculate rainfall intensity for this assessment.

Table 4.6 Rainfall duration and Intensity

Rainfall Duration	**Rainfall Intensity**
0.5 hr	67.58 (mm/h)
1hr	41.1 (mm/h)
2hr	24.84 (mm/h)
3hr	18.49 (mm/h)
6hr	11.14 (mm/h)
12hr	6.70 (mm/h)

Table 4.6 indicates the relationship between rainfall duration and intensity. Rainfall duration is changing from 0.5 hr., to 12 hr., rainfall intensity decreases from 67.6 to 6.7 mm/h. Rainfall duration increases when rainfall intensity decreases for a design rainfall event.

D.) Calculation of peak discharge

Peak discharge was calculated by using rainfall intensity, surface runoff coefficient, and catchment area parameters. After calculation rainfall intensity by using the ReFH rainfall–runoff model and FEH CD-ROM v 3.0 (CEH, 2009) software, peak flow (Q) was computed for both Modified Rational method (Chadwick et al., 2004) and Rational method (Houghton-Carr, 1999) approaches.

Table 4.7 Peak flows (Q) from different rational methods

Method	Modified Rational Method	Rational Method
($URBEXT_{1990}$)	1.04(m^3/s)	1.7(m^3/s)
($URBEXT_{2016}$)	2.0(m^3/s)	3.4(m^3/s)

Peak flows (m^3/s) were compared between Modified Rational Method (Chadwick et al., 2004) and Rational Method (Houghton-Carr, 1999) of the 1 in 100-year event (Table 4.7). It is observed that peak flow values of the rational method (Houghton-Carr, 1999) are higher than the values of the modified rational method (Chadwick et al., 2004). The impact of peak flow on the discharge and on the fluvial flood risk of the Lower Wortley Beck can be observed better in the rational method (Table 4.7). Therefore, the rational method (Houghton-Carr, 1999) was chosen to assess the fluvial flood risk for various situations such as frequency, land use change, and rainfall duration in this research.

Table 4.8 Peak Flow (Q) from Rational Method for different return periods and URBEXT values

Return period	15 yr.	50 yr.	100 yr.
Peak flow (Q) $URBEXT_{1990}$ (0.13)	1(m^3/s)	1.4(m^3/s)	1.7(m^3/s)
Peak flow (Q) ($URBEXT_{2016}$) (0.22)	1.97(m^3/s)	2.8(m^3/s)	3.4(m^3/s)

Peak flow values (Q) (m^3/s) for each URBEXT values and return periods can be found in Table 4.8. When the ratio of the impermeable surfaces increases, the response time of the catchment (time to peak, Tp) can be smaller, so that runoff can be faster.

In addition, when the ratio of the impermeable surfaces increases, the design rainfall duration decreases, and peak flow increases. It is obvious that when the rainfall return period increases, peak flow values increase.

The crucial outcome from this table is that the peak discharge from high-urbanised catchments with long return periods can cause serious flood risk.

Table 4.9 Peak Flow (Q) (m^3/s) from Rational Method for different rainfall duration (h) and return periods (yr)

Rainfall Duration	**Q 15 yr.**	**Q 50 yr.**	**Q 100 yr.**
0.5 hr	2.9(m^3/s)	4.3(m^3/s)	5.4(m^3/s)
1hr	1.8(m^3/s)	2.6(m^3/s)	3.3(m^3/s)
2hr	1.15(m^3/s)	1.6(m^3/s)	1.97(m^3/s)
6hr	0.55(m^3/s)	0.74(m^3/s)	0.88(m^3/s)

Peak flow values (Q) (m^3/s) were assessed for various rainfall durations (hr) and return periods (yr) (Table 4.9). Table 4.9 displays that rainfall duration increases, peak flow decreases, when the return period (yr.) is constant. Return period increases from 15 yr. to 100 yr., peak flow increases, when the rainfall duration (hr) is constant. The primary outcome from this table is that peak discharge from longer rainfall duration events can be lower, but a short rainfall event can cause high rainfall intensity for design rainfall events and so high peak flow can be observed. Therefore, short but high-intensity rainfall event may cause flash flooding, backwater effect and pluvial flooding in the sub-catchment area.

4.3.1 Results of fluvial flood inundation area and water depth

The results of this chapter were used to assess fluvial flood risk of the Lower Wortley Beck. The fluvial flood risk was assessed by using the flood inundation area, the percentage of water depth values and flood inundation maps. The fluvial flooding at the Lower Wortley Beck area was simulated by integrated the lateral inflow from New Farnley basin with the inflows from the Farnley Beck and Farnley Wood Beck basins, in this chapter.

Inflow hydrographs from Farnley Beck and Farnley Wood Beck sub-catchments were plotted by using ReFH rainfall-runoff model. The lateral inflows were calculated by using the rational method of the Houghton-Carr (1999). The 1D/2D fluvial hydrodynamic model was used for the simulations. During these simulations, the input data of sub-catchments were designed for the constant rainfall return period, rainfall duration, and the URBEXT values in the whole catchment. Inflow hydrographs, sub-catchments, and the hydrodynamic model were explained in detail in fluvial flood event chapter.

The outcomes were produced for various design events. These model simulations were performed for the URBEXT value of the 1990-year, and the URBEXT value of the 2016-year for the 15, 50 and 100-year return periods. In addition, these model simulations were performed for the rainfall durations were 0.5-hr., 1-hr., and 6-hr. The impact of the ratio of the impermeable surface (URBEXT) was used to assess the urbanisation. The impact of the rainfall frequency and rainfall duration were applied to assess the rainfall-runoff process of the sub-catchment.

A.) Flood inundation area

The effects of impermeable surfaces (URBEXT values), the return periods, and the rainfall durations were assessed on the flood inundation areas in this section (Figure 4.2, Figure 4.3, and Figure 4.4). Flood inundation area is at the Lower Wortley Beck area.

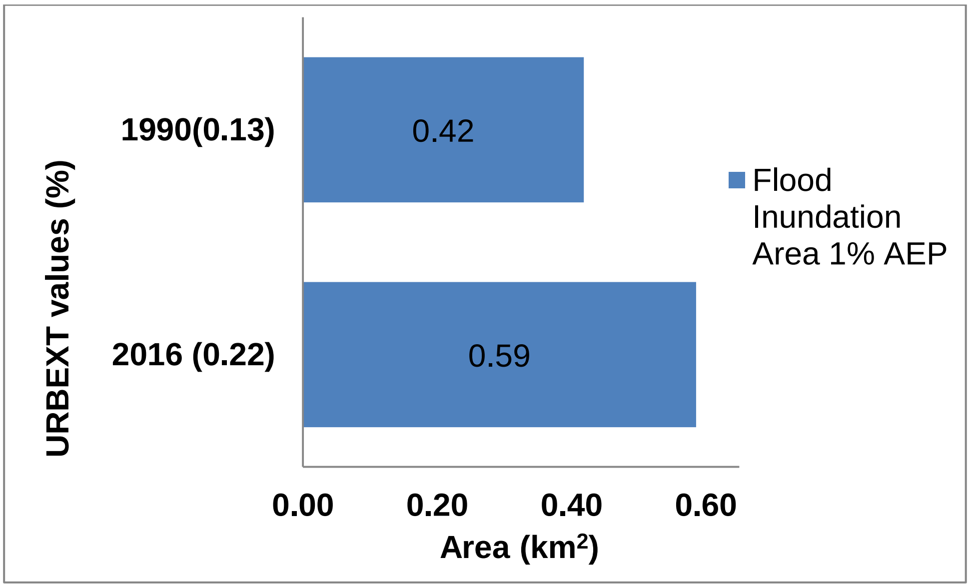

Figure 4.2 Urbanisation and flood inundation area

The interaction between the URBEXT value of sub-catchment and flood inundation area was assessed in Figure 4.2 for the 1 in 100-year event of peak flow.

The impact of the ratio of the impermeable surface (URBEXT) of the New Farnley was assessed to analyse fluvial flood risk of the Lower Wortley Beck. The values of $URBEXT_{1990}$ and $URBEXT_{2016}$ were 0.13 and 0.22 respectively for this assessment. Flood inundation area is 0.42 km^2 for the $URBEXT_{1990}$ and 0.6 km^2 for the $URBEXT_{2016}$ for 1 % AEP flood event.

Figure 4.2 displays that when the ratio of impermeable surface increases by urbanisation or decreases by the sustainable urban drainage system, these situations can have an impact on maximum discharge and the downstream fluvial flood risk.

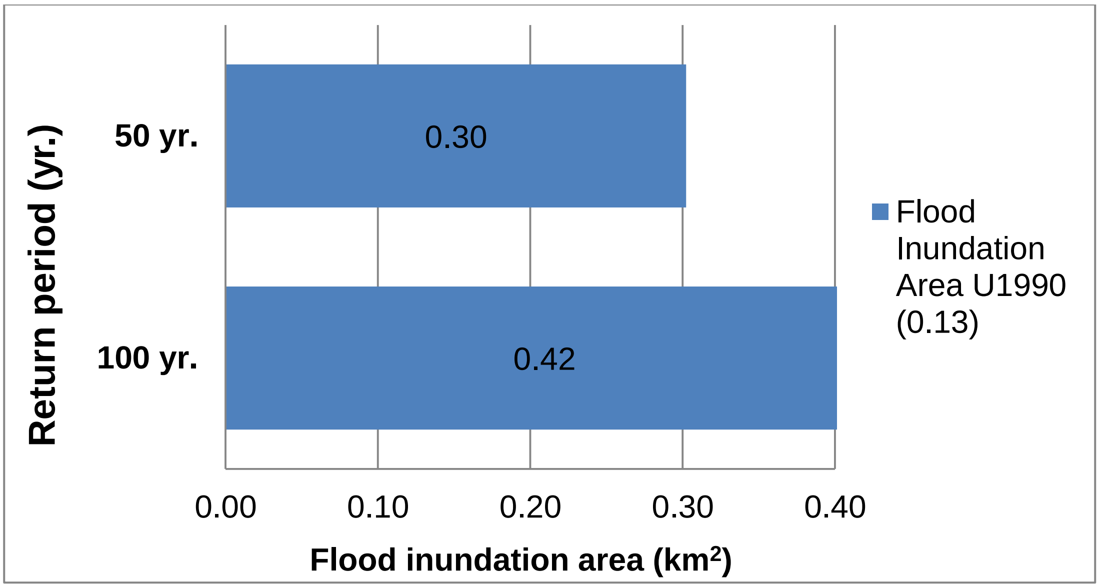

Figure 4.3 Return period and flood inundation area

The interaction between the return period (yr.) of peak flow and flood inundation area was assessed in Figure 4.3. The ratio of the impermeable surface ($URBEXT_{1990}$) of the New Farnley was used. The return period of the peak flow was changed from 100 yr. to 50 yr., fluvial flood inundation area of the Lower Wortley Beck changed from 0.4 km^2 to 0.3 km^2.

Figure 4.3 displays that the magnitude of the rainfall event can have an impact on the maximum discharge value and the downstream fluvial flood risk.

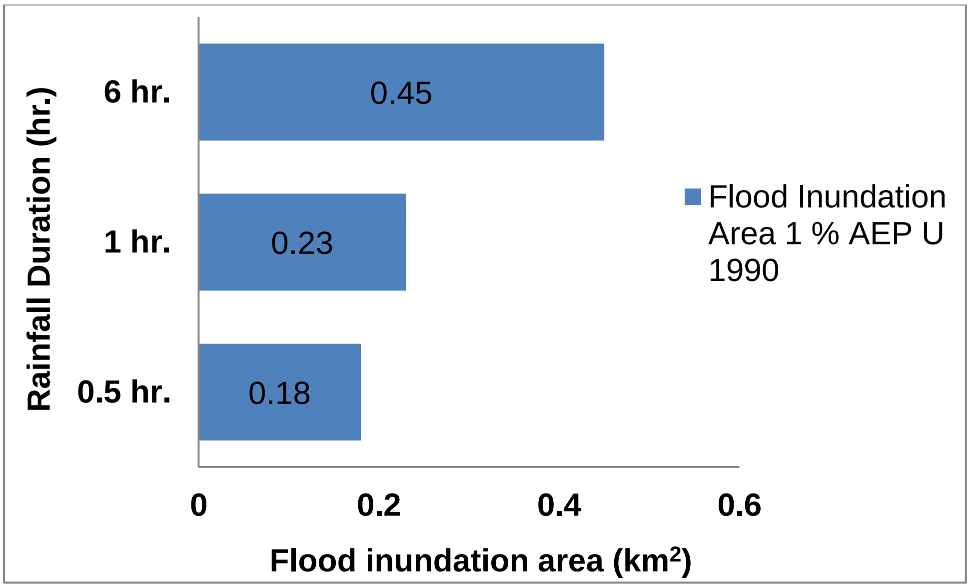

Figure 4.4 Rainfall duration and flood inundation Area

The interaction between the rainfall duration (hr.) and flood inundation area (km^2) was assessed in Figure 4.4. The ratio of the impermeable surface ($URBEXT_{1990}$) of the New Farnley and the 1 in 100-year event were used for simulation. The rainfall duration was changed from 0.5 hr. to 1 hr. and to 6 hr., so that the fluvial flood inundation area of the Lower Wortley Beck changed from 0.18 km^2 to 0.23 km^2 and to 0.45 km^2 respectively.

Figure 4.4 displays that the rainfall duration can have an impact on the maximum discharge and the downstream fluvial flood risk.

B.) The percentage of water depth values

The effects of the URBEXT values, the return periods and the rainfall durations on the ratio of water depth values in flood extent of the Lower Wortley Beck area were assessed in this section (Figure 4.5, Figure 4.6, and Figure 4.7).

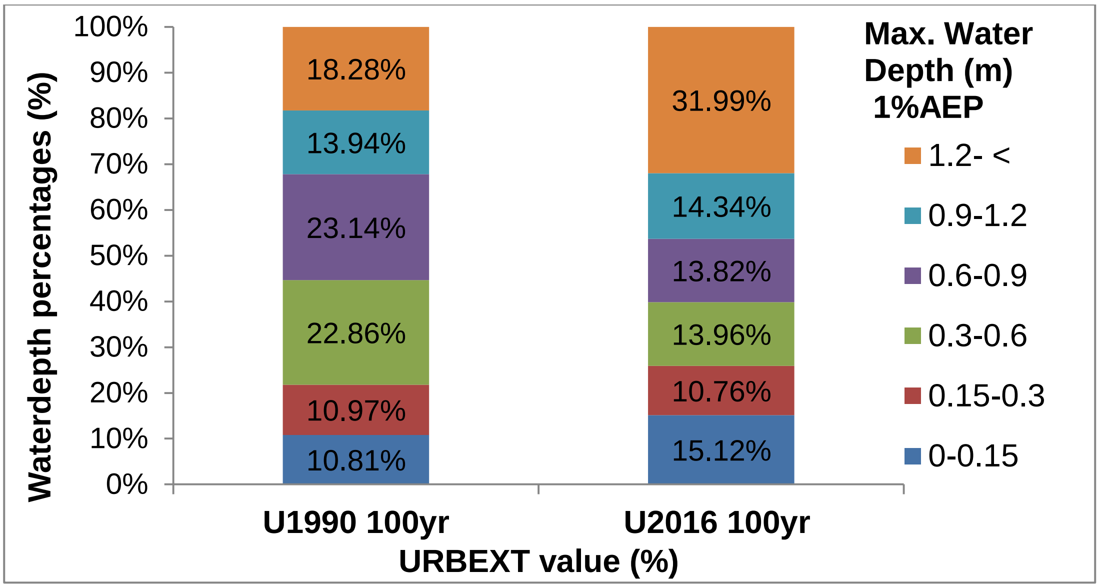

Figure 4.5 Water depth percentages (%) and urbanisation

Figure 4.5 displays the percentages of water depth (m) in a flood inundation area for $URBEXT_{1990}$ and $URBEXT_{2016}$ values. The water depth becomes higher when the ratio of the impermeable surface of the sub-catchment becomes larger.

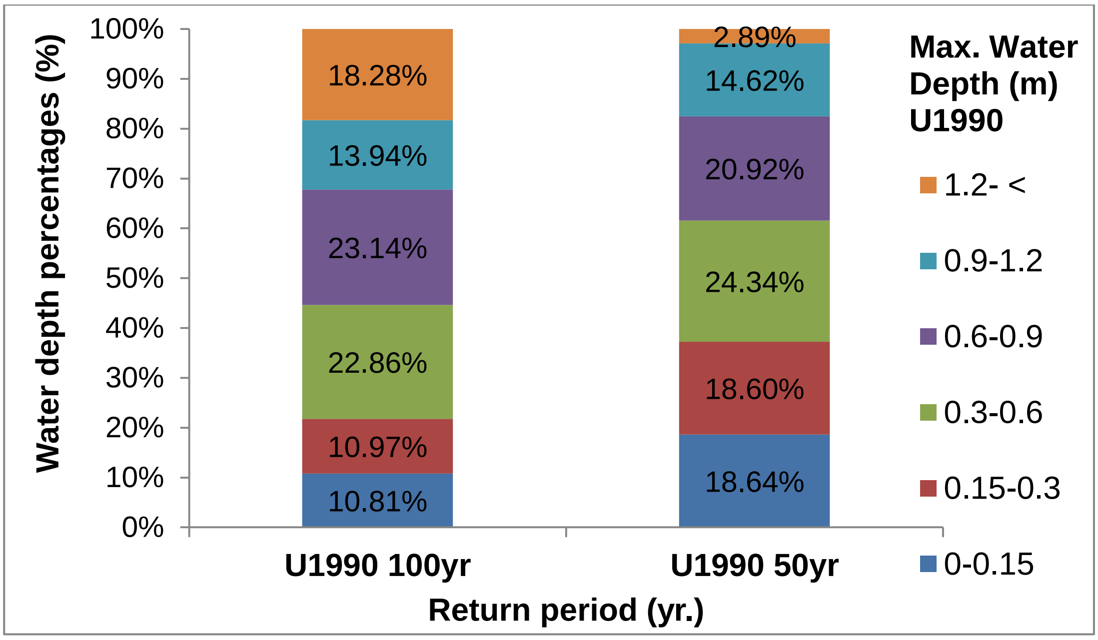

Figure 4.6 Water depth percentages (%) and rainfall return period (yr.)

Figure 4.6 displays the percentages of water depth (m) values for return period of the catchment of the 1 in 100-year and 1 in 50-year event. The water depth becomes higher when the return period of the peak flow becomes longer.

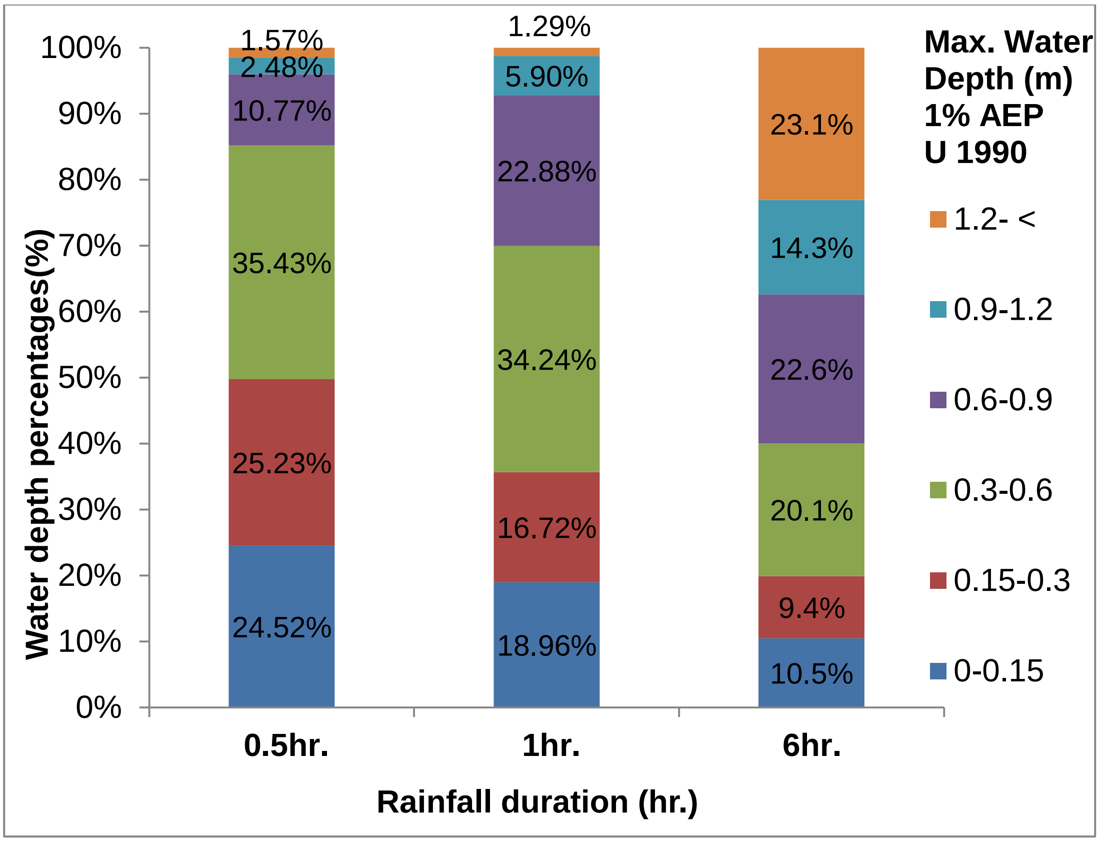

Figure 4.7 Water depth percentages (%) and rainfall duration (hr.)

Figure 4.7 displays the percentages of water depth (m) values for rainfall duration of 0.5 hr., 1 hr., and 6 hr. The water depth becomes higher when the rainfall duration of the rainfall event in the catchment becomes longer.

C.) Probabilistic flood Inundation Maps

Probabilistic flood inundation maps were examined in this section. Figures (4.8, 4.9, 4.10, 4.11, and 4.12) display the flood inundation area at the Lower Wortley Beck location for the probability of occurrence of the flood event is the 1 in 100-year event. These flood inundation maps display the flood events for the URBEXT value of the 1990 year, and the URBEXT value of the 2016 year in the catchment. In addition, flood inundation maps were produced for various rainfall durations (0.5 hr., 1hr., and 6 hr.) of rainfall event in the catchment. Rational method (Houghton-Carr, 1999) was used to estimate the peak discharge from New Farnley sub-catchment. The ReFH rainfall-runoff method was used to estimate the inflows from FB and FWB sub-catchments. The background of Figures (4.8, 4.9, 4.10, 4.11 and 4.12) were produced by using OS 1:25 000 Scale Colour Raster and contain OS data © Crown copyright and database right (2015) (Ordnance Survey, 2015). Arc MAP 10.2.2 tool was used to produce these maps.

1.) URBEXT $_{1990}$ 1 % AEP

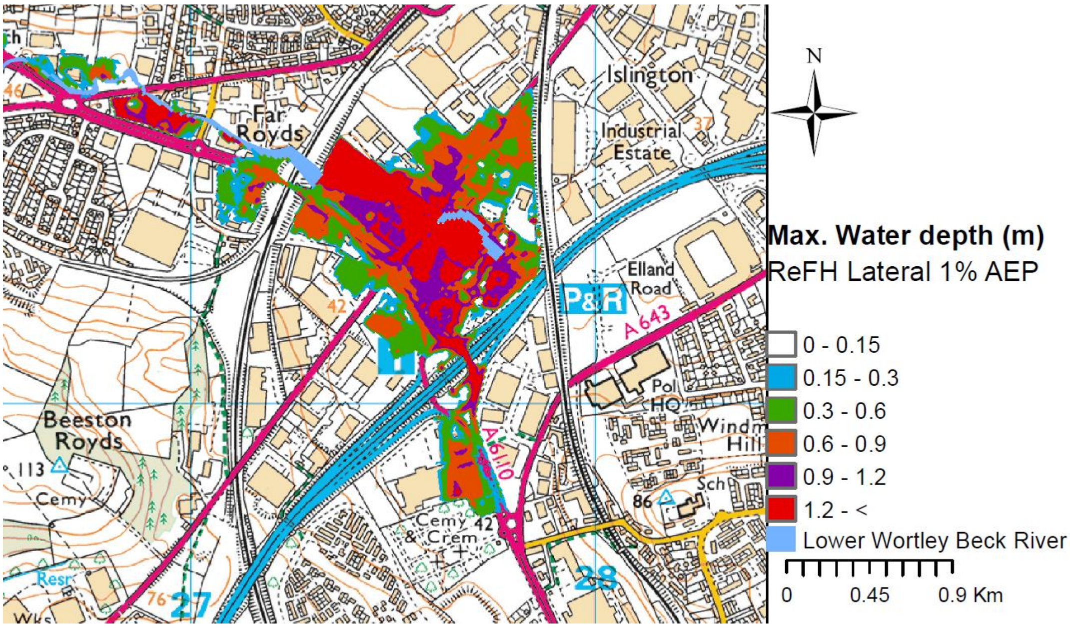

Figure 4.8 URBEXT $_{1990}$ 1 % AEP

Flood inundation area in Figure 4.8 displays the flood event for URBEXT value year of 1990.

2.) URBEXT $_{2016}$ 1 % AEP

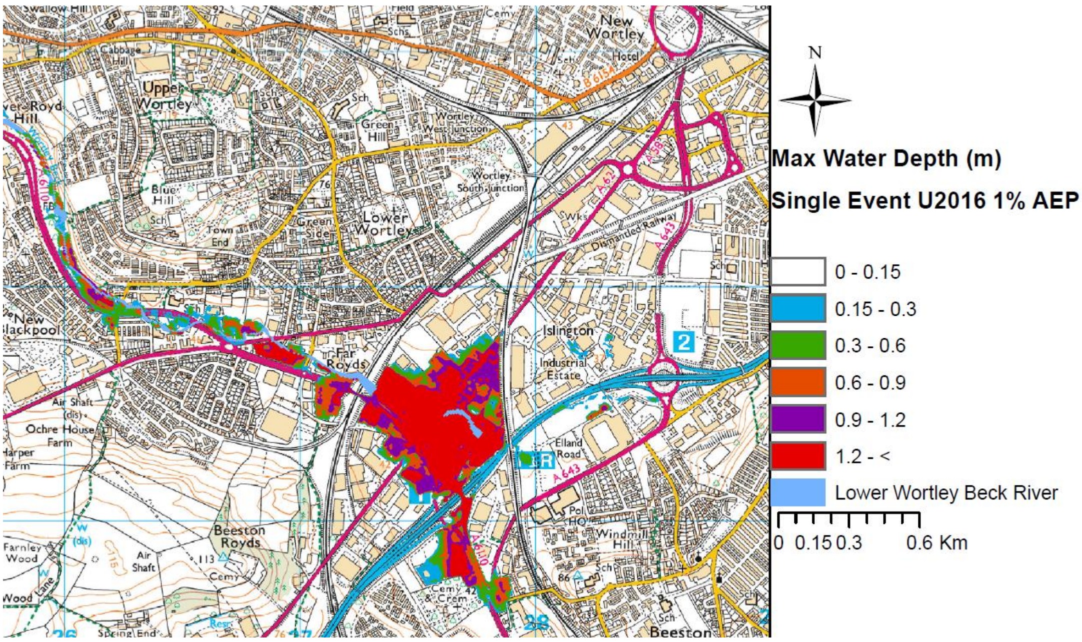

Figure 4.9 URBEXT $_{2016}$ 1 % AEP

Flood inundation area in Figure 4.9 displays the flood event for URBEXT value year of 2016.

The urbanisation parameter can affect both catchment response time in the sub-catchments and flood extent at the downstream

3. URBEXT $_{1990}$ 1 % AEP for 0.5 hour rainfall duration

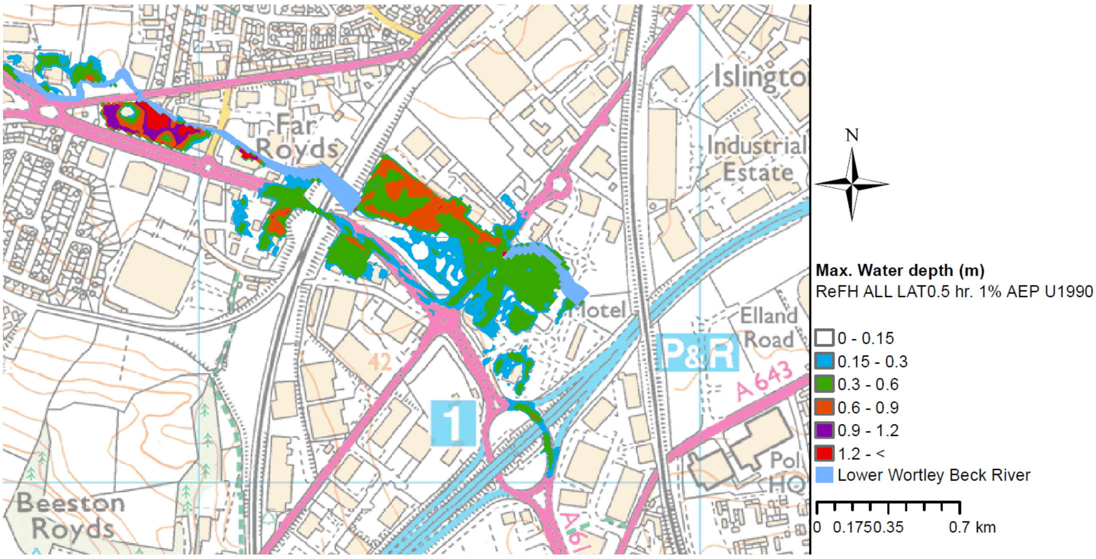

Figure 4.10 URBEXT $_{1990}$ 1 % AEP for 0.5 hour rainfall duration

Figure 4.10 displays the flood event of the rainfall duration 0.5 hr., for all the catchment with the urbanisation of the 1990-year. Flood extent area is 0.18 km^2.

4. URBEXT $_{1990}$ 1 % AEP for 1 hour rainfall duration

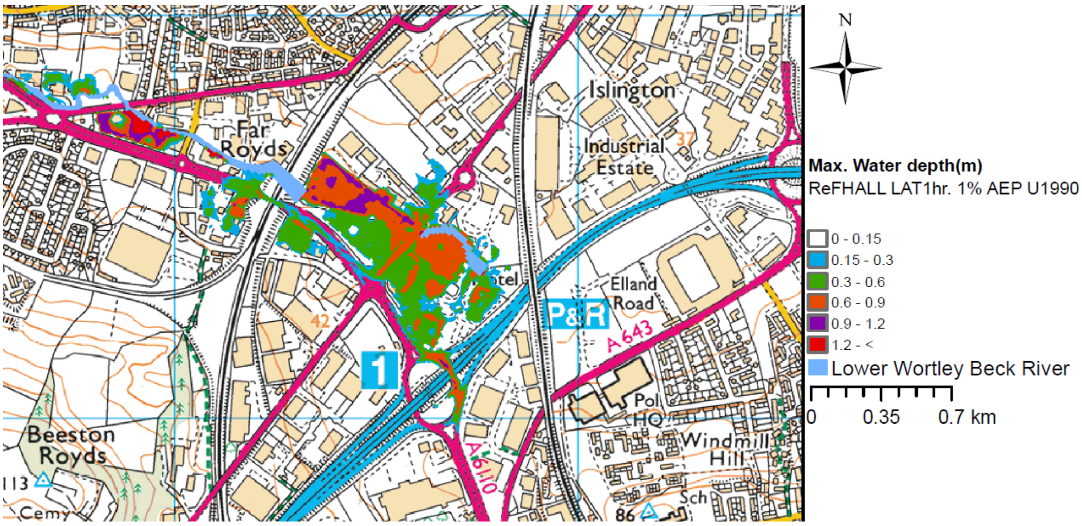

Figure 4.11 URBEXT $_{1990}$ 1 % AEP for 1 hour rainfall duration

Figure 4.11 displays the flood event of the rainfall duration 1 hr., for all the catchment with urbanisation of the 1990-year. Flood extent area is 0.23 km^2.

5. URBEXT$_{1990}$ 1 % AEP for 6 hour rainfall duration

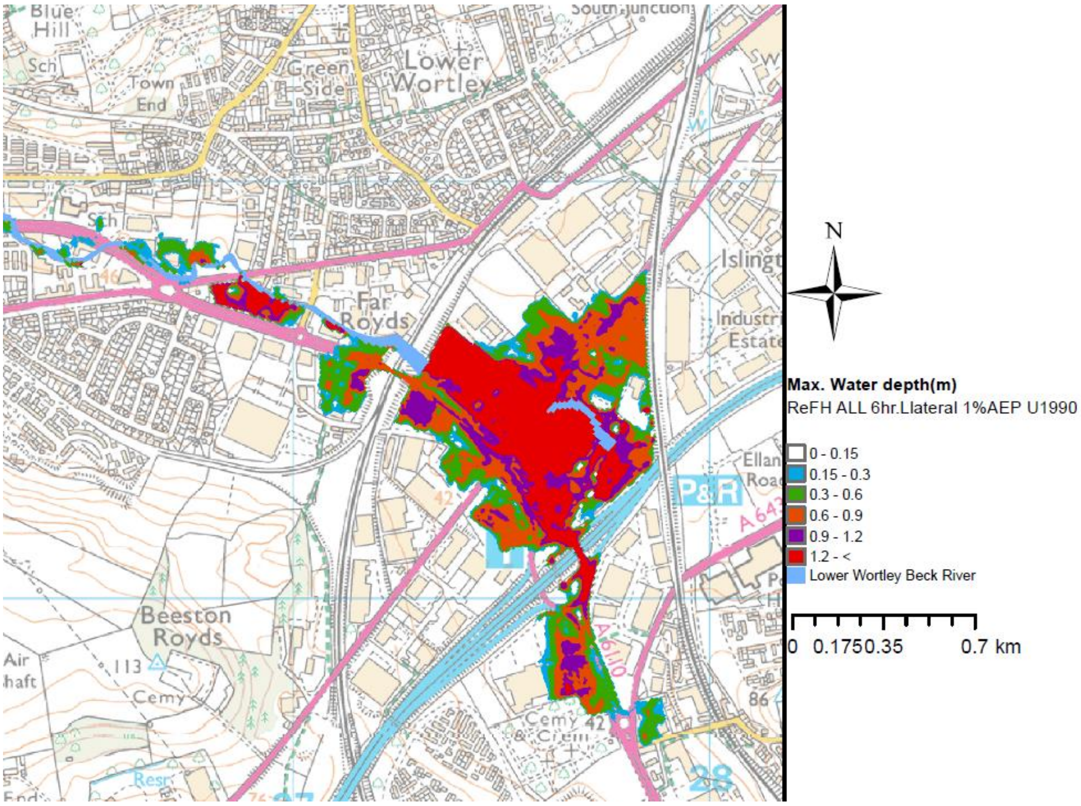

Figure 4.12 URBEXT$_{1990}$ 1 % AEP for 6 hour rainfall duration

Figure 4.12 displays the flood event of the rainfall duration 6 hr., for all the catchment with urbanisation of the 1990-year. Flood extent area is 0.45 km^2.

Results of the design flood events were produced for the same return period and URBEXT value in the Wortley Beck catchment. In addition, the rainfall durations were changed from 0.5 hr., to 1 hr., and to 6 hr.

Results indicate that when the rainfall durations are changed from 0.5 hr., to 6 hr., inflow hydrograph becomes greater, and peak flow becomes smaller. In addition, when the rainfall durations are changed from 0.5 hr., to 6 hr., the flood extent area becomes greater, and the water depth becomes higher.

The outcomes show that the area of the flood extent becomes larger. Flood inundation areas are 0.18 km^2, 0.23 km^2, and 0.45 km^2 respectively. The reason of this can be that longer rainfall duration is significant for fluvial flood risk whereas short with high-intensity rainfall event can be more significant for pluvial flooding in urbanised catchments.

Lastly, the main flood risk areas in the Lower Wortley Beck area could be Gelderd road and A6110 transportation link, and Leeds train station. Flood risk mitigation approaches such as sustainable urban drainage systems in the upstream catchment can be used to retard the surface runoff and to attenuate the downstream flood risk for large river basins (de Kok and Grossmann, 2010; Du et al., 2015).

4.4 Conclusion

The relationship between maximum discharge and downstream fluvial flood events was assessed in this chapter. The maximum discharge that drains into the river channel from a sub-catchment was observed for this assessment. It was integrated as a lateral flow with the Lower Wortley Beck fluvial system. This lateral flow represents the peak flow at the outlet of the New Farnley Beck basin. The flooding at the downstream area can be affected by the properties of the surface and the rainfall intensity in the New Farnley Beck basin. The interaction between surface overflow and fluvial flood risk at the downstream was analysed by using the ratio of impermeable surfaces and rainfall event duration in this research.

The lateral flow was computed by using the rational method in this research. However, in literature, this method has been mostly used to estimate peak flow in the design of urban drainage systems. The rational method calculation has three main parameters. These are surface runoff coefficient, rainfall intensity, and basin area. To calculate peak flow, rainfall intensity was computed from a Depth (mm) /Duration (hr.)/ Frequency (T, return period year) curve by using FEH software version 3.0 by NERC (CEH, 2009). However, the D/D/F curve can only allow estimation of the peak flow for the same defined return period of a rainfall event.

To investigate the fluvial flood risk at the downstream of Wortley Beck catchment and to produce probabilistic flood inundation maps, the coupled 1D (Flood Modeller Suite) / 2D (TUFLOW) hydrodynamic model was linked with GIS software. Both rainfall event and the impermeable surfaces in the sub-catchments influence the flood peak magnitude and arrival time.

1. The impact of the ratio of impermeable surfaces on the peak flow was investigated to assess the urbanisation.

The URBEXT value was used to observe the impact of the impermeable surfaces of the New Farnley on the peak flow. When the ratio of the impermeable surface increases, the catchment response time decreases, because the surface runoff becomes faster. This can cause high peak flow; as a result, a higher discharge value can be seen, causing a large flood extent downstream.

2. The impact of rainfall duration on the peak flow was investigated to observe the discharge.

Inflows from Farnley Beck and Farnley Wood Beck sub-catchments and peak discharge from New Farnley sub-catchment were estimated for the same rainfall durations, the same return periods, and the same urban extents in the whole basin. Rainfall duration has a significant impact on peak flow. Short rainfall duration causes high rainfall intensity.

When the URBEXT and return period are constant, and rainfall duration is increased to estimate peak flow and inflow hydrographs, rainfall intensity becomes lower, peak flow becomes lower, but inflow hydrograph becomes greater. Inflow hydrograph becomes longer with longer rainfall durations. The flow of the inflow hydrograph becomes higher, so that even when peak flow is low at the outlet of the New Farnley Beck basin, the flood extent area becomes larger, water depth becomes higher, and downstream flood risk increases.

Longer rainfall duration is significant for fluvial flood risk whereas short with high-intensity rainfall event can be more significant for pluvial flooding in urbanised catchments.

3. The impact of return period on peak flow, when the URBEXT value and the rainfall duration are constant, shows that as the return period increases, rainfall intensity increases, peak flow increases, and flood extent increases with higher water depth values.

In summary, increasing in rainfall intensity and impermeable surfaces can cause great overflows.

Rainfall duration is effective on water depth and flood extent, but the impact of urbanisation on flood events is the most significant one. Moreover, short duration but high-intensity rainfall on an urbanised basin can cause a serious of high-level peak flow. Therefore, this event can be the source of a pluvial flooding in the basin. When the rainfall duration increases, this can cause a low level of rainfall intensity and so a small magnitude of peak flow, but fluvial flood risk is higher at downstream location.

Due to the methodology, the application of this method has a number of inherent assumptions. The assumptions could cause some limitations in the calculation. Rainfall intensity cannot be uniform during the event but peak flow was applied as constant in the basin. The runoff coefficient or antecedent soil moisture was accepted as constant over the basin during the rainfall event. Drainage loss and the influence of basin storage were not considered. The basin surface was assumed homogeneous. These could cause the estimation of the maximum discharge becomes greater in this research.

Consequently, this project assesses the impact of urbanisation and rainfall duration on the rainfall-runoff process of the upstream. Peak flow calculation was used to assess surface overflow in the New Farnley area. The surface overflow in the sub-catchment can be the source of the urban drainage outfall as maximum discharge into the river channel. The discharge efficiency of the urban drainage system, the ratio of impermeable surfaces, and rainfall intensity could create an interaction between the pluvial flooding and fluvial flooding. Sustainable urban drainage systems (SUDS) can be used in the urbanised catchment to decrease and retard runoff. Flood risk mitigation approaches in the upstream catchment can be applied to decrease the downstream flood risk.

Chapter 5 Pluvial Flood Modelling

5.1 Introduction

This chapter introduces an assessment of the pluvial flooding in the Wortley Beck catchment, Leeds. The pluvial flooding can be observed in a combination of high-intensity rainfall events, limited urban drainage systems capacity, and limited permeable surfaces in urban areas. Surface runoff and ponds could occur, when rainfall could not be infiltrated by the saturated ground and could not be managed by the drainage system in urban areas (Falconer et al., 2008; Pitt, 2008; Falconer et al., 2009; Morris et al., 2009; Kellagher et al., 2010; Houston et al., 2011; Falconer and Smyth, 2012; Jha et al., 2012). Pluvial flood events can occur in a short time; therefore, it is difficult to warn, and to detect the vulnerable places with in a sufficient lead-time (Pitt, 2008; Houston et al., 2011).

Pluvial flood events were observed in many locations including in Newtownards, Comber, Omagh, Magherafelt, and Belfast in Northern Ireland, Newcastle West, in England, and Dublin in Ireland. Some pluvial flood events were observed in Glasgow, Scotland in 2002. Similarly, pluvial flood events were observed in Hull and other parts of the UK in summer 2007 (Falconer et al., 2008; Morris et al., 2009). One-third of flood risk in the UK is a result of pluvial flooding (Houston et al., 2011).

The consequences of pluvial flooding can be severe, due to the physical damage to property and due to the disruption to daily life in heavily built urban areas. Moreover, when rainfall exceeds the capacity of the drainage system, the effects of pluvial flooding can be the health hazard to the public due to the contaminated surface water with foul sewage (Falconer et al., 2009). Vulnerable places can be residences, industrial locations, rail stations, infrastructure systems, and transportation links in the urban areas (Houston et al., 2011; Falconer and Smyth, 2012).

These consequences can be much more adverse in the future due to urbanisation and climate change. These factors can result in faster and larger magnitude runoff in urban areas so it is difficult to manage runoff with urban drainage systems.

According to the annual growth projections, population growth can anticipate as between 1% and 1.5% (Falconer and Smyth, 2012). Around three times more population can be at surface flood risk due to the population growth in the urban areas than due to climate change, by 2050, in the UK (Houston et al., 2011).

5.1.1 The suitability of Wortley Beck catchment

Wortley Beck catchment is an ungauged and urbanised catchment. The population growth and valuable investment in the flood risk locations can make the Wortley Beck catchment vulnerable. Moreover, The Environment Agency confirmed that this area (Figure 5.1) Lower Wortley has a severe level surface flood risk (Environment Agency, 2013). Therefore, flood risk should be managed as soon as possible, and flooding is a research priority for the Wortley Beck catchment.

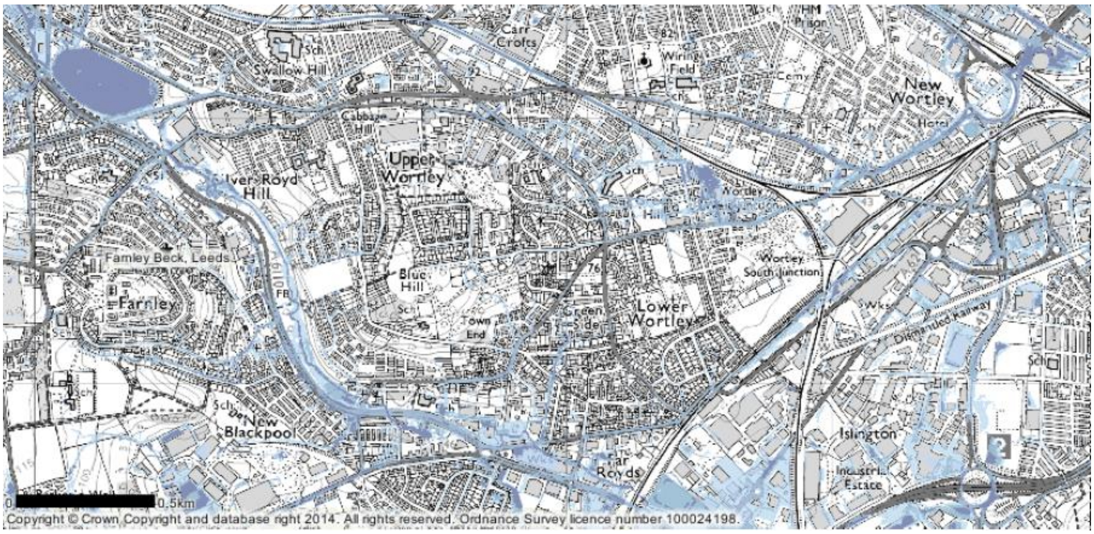

Figure 5.1Lower Wortley surface flood risk (Environment Agency, 2013 RFI no: 29864)

5.2 Methodology of the pluvial flooding

The simulation methodology of the pluvial flood modelling for the Wortley Beck catchment is explained in this section. The Wortley Beck catchment can be seen in Figure 5.2. Pluvial flooding was assessed by using a 2D direct rainfall method.

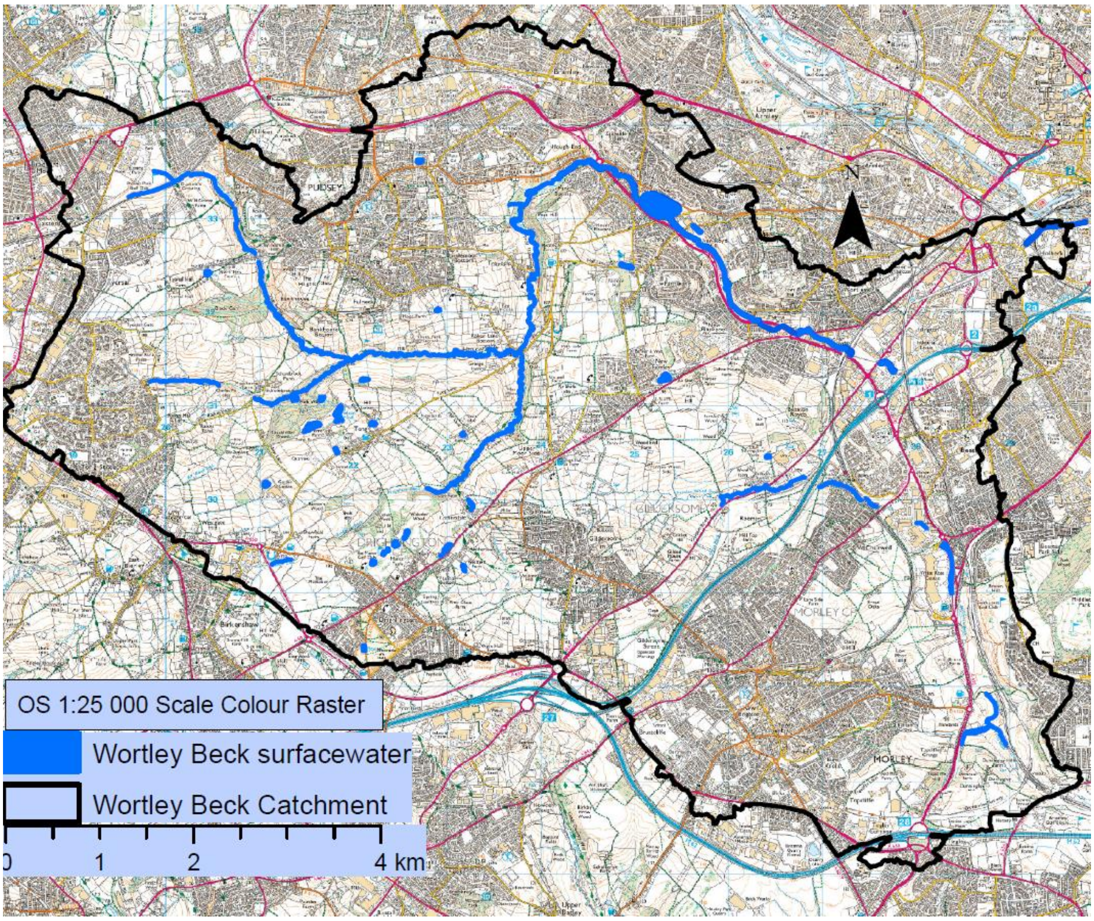

Figure 5.2 The Wortley Beck Catchment (WBC)

5.2.1 Direct rainfall method

The Direct Rainfall Model (DRM) is a relatively new approach and can replace traditional rainfall-runoff processes (Engineers Australia, 2012; Boyte, 2014; Hall, 2015). The traditional flood modelling approach consists of hydrological and hydraulic analysis. Hydrological models can generate peak flows significantly faster than direct rainfall models but to build a traditional hydrologic model can take longer time (Engineers Australia, 2012). This approach uses only one model, the rainfall event is applied over the 2D domain for the entire catchment without using any hydrological routing model and runoff can be observed on the 2D flow pathways of the research area (Engineers Australia, 2012). Therefore, this modelling approach does not require the estimation of flow at discrete locations because the flow is automatically generated from the rainfall event, so that the hydrological routing process can be partially or completely removed from the modelling in the direct rainfall approach (Davin et al., 2011; Engineers Australia, 2012; Johnson, 2015). Rehman et al. (2003) discovered that the DRM has longer runoff times than Lumped conceptual models. Caddis et al. (2008) and Clark et al. (2008) supported this (Johnson, 2015). The 2D model uses the entire catchment area so model run times could be longer, high-quality terrain data and aerial survey data are necessary as well (Engineers Australia, 2012; Hall, 2015). Nevertheless, it could be said that a direct rainfall model with good quality topographic basin data and drainage system data could indicate more realistic outcomes than the traditional rainfall-runoff models (Engineers Australia, 2012).

5.2.2 TUFLOW 2D hydrodynamic surface flooding model

The direct rainfall method was applied by using Two-Dimensional Unsteady Flow (TUFLOW) hydrodynamic modelling package software. The version of software was TUFLOW (2013-12-AD-w64) “Classic”. It uses a CPU based second order semi-implicit solution (BMT WMB, 2016). The reason for the selection of the TUFLOW 2D hydrodynamic model for direct rainfall modelling was that the software could simulate the overland flow pattern of the catchment from direct rainfall data input. In addition, the TUFLOW software can be used to assess the impact of urbanisation, to compute water level and peak flow in the research area. This is very useful for ungauged catchments.

The software solves the full two-dimensional depth averaged shallow water equations to produce flow and water depth values for each rainfall events and probabilistic flood inundation maps. The theory was implemented within the program by BMT WBM Pty Ltd and The University of Queensland in 1990 (Syme, 2001; BMT WMB, 2016). Later, a 2D/1D dynamically linked, an advanced 2D/1D, 2D/2D linked modelling system, and Geographic Information System (GIS) link application system were developed and integrated into this (Syme, 1992; Syme, 2001; BMT WMB, 2016). TUFLOW has been tested and validated in many published research studies, for example, Barton, 2001; Huxley, 2004; Néelz and Pender, 2013 (BMT WMB, 2016).

5.2.3 Build-up process of the direct rainfall model

To simulate pluvial flooding in the Wortley Beck catchment, main input data was the rainfall hyetograph. However, TUFLOW does not have a UK rainfall generator built in, so the rainfall has to be generated separately and put into the model manually. Net rainfall data was the first input of the modelling process. The format was rainfall depth (mm) for per time step (hour). The net rainfall hyetograph was estimated by using loss model section of the Revitalised boundary unit of the Flood Modeller Suite tool. Interception, evaporation, depression storage, and infiltration are excessed from gross rainfall data to define the net rainfall. The net rainfall hyetograph was applied on the permeable and impermeable surfaces of the Wortley Beck Catchment (WBC). Two kinds of rainfall input data were used for this modelling. These were the measured rainfall data and design rainfall event data. The measured rainfall data was taken from the Environment Agency.

A LiDAR data and master map data of WBC were the second input data, and used to simulate the surface runoff. The LiDAR data with 2 m resolution was used to assess elevation of the catchment (Figure 5.5), the master map was used to assess feature of the land surfaces in Figure 5.6 Impermeable surfaces in the Wortley Beck catchment. In addition, the roughness values of the land surface materials can be found in Table 5.3 Land use materials.

These data sets for the Wortley Beck catchment were obtained from the Environment Agency. A 2D (TUFLOW) hydrodynamic modelling tool was used for the interaction between rainfall data and topographical data.

Lastly, model run time was the final input. Figure 5.3 displays the steps of the build-up the pluvial flood model. Figure 5.4 displays the framework of direct rainfall- runoff model for TUFLOW.

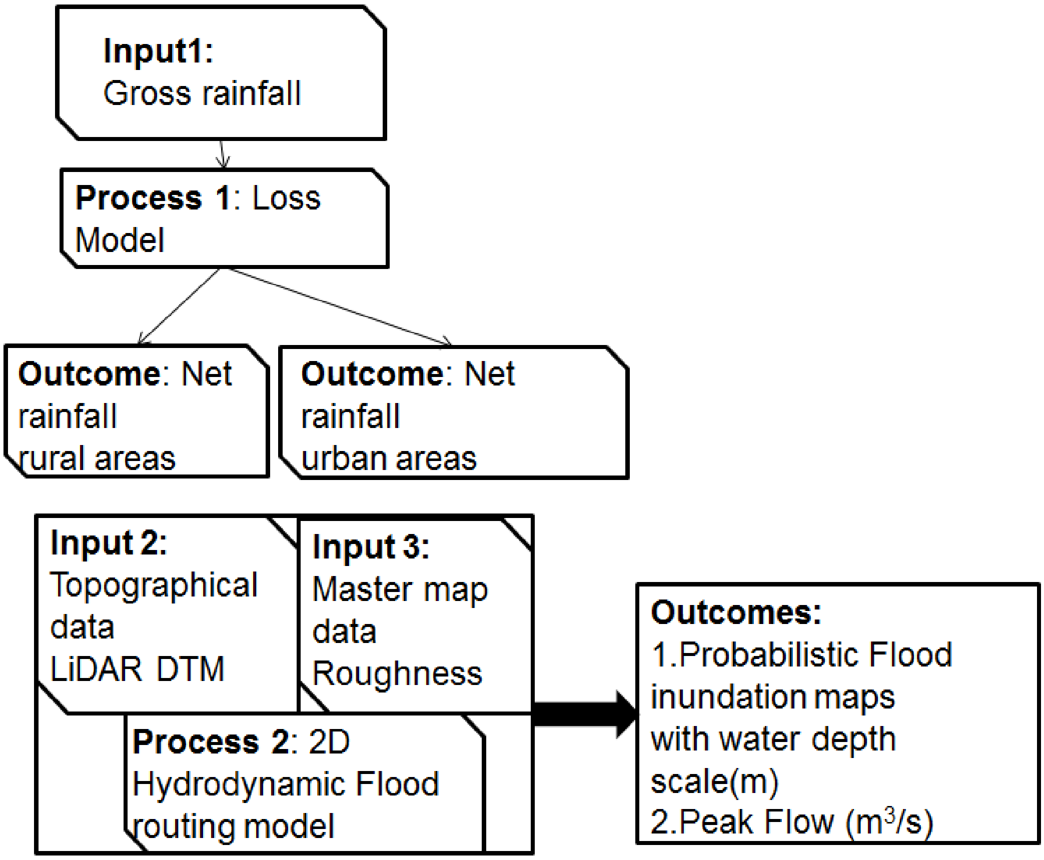

Figure 5.3 2D Hydrodynamic direct rainfall-urban surface flood-modelling approach

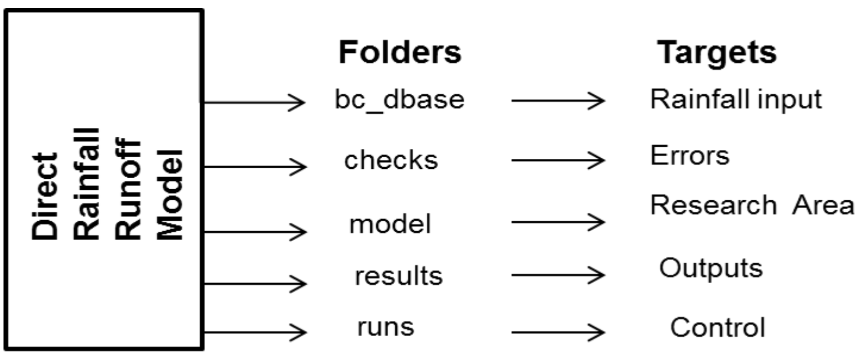

Figure 5.4 Framework of direct rainfall- runoff model for TUFLOW

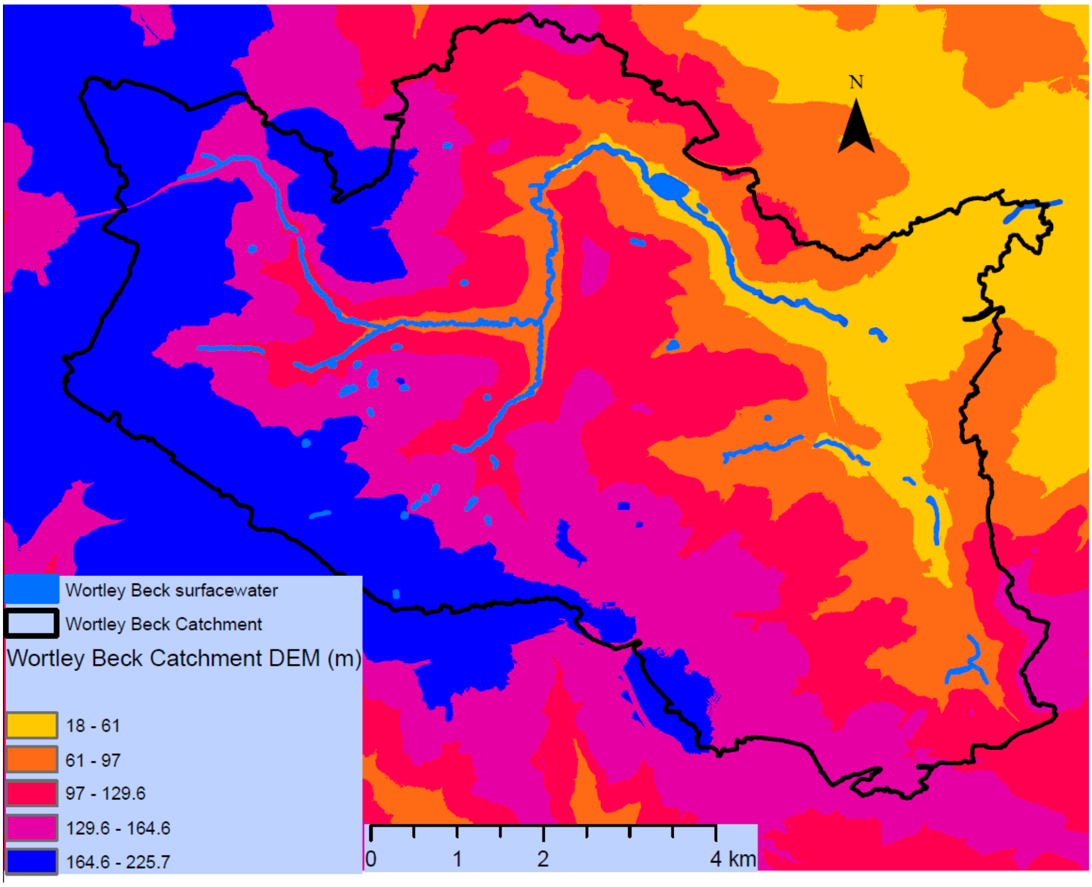

Figure 5.5 The DEM of the Wortley Beck Catchment (WBC)

The model was run for 10 m and 5 m cell resolutions. As cell size becomes smaller, the model-run time significantly increases (Hall, 2015). However, model cell size should be smaller than 10m (Clark et al., 2008). Model cell size 5 m resolution was found to be suitable for the evaluation of the results in this research.

The function of sewer drainage was neglected in this methodology. The outcomes of this model were analysed by using probabilistic flood inundation maps with maximum water depth (m), water level (m AOD), and peak flows (m^3/s) so that vulnerable areas were determined. These outcomes were produced by using the (1 in 5 yr., 15 yr., 30 yr., 50 yr., and 100 yr., also 0.5 hr., 1hr., and 6hr., of a 100-year return period) rainfall events for the Wortley Beck catchment (WBC).

5.2.4 Estimation of the rainfall events for the pluvial flood risk assessment

In this section, the calculation of a hyetograph for the pluvial flood modelling is explained. The Wortley Beck catchment did not have sufficient recorded rainfall data to estimate rainfall events. As a result, the net rainfall hyetograph was produced by using the ReFH boundary (ReFHBDY) unit of the Flood modeller suite. The net rainfall hyetograph was calculated for impermeable and permeable surfaces of the Wortley Beck catchment, by using ReFH loss model. The FEH techniques accounting for infiltration losses could be applied either implicitly (in the case of the statistical method) or explicitly (using ReFH) (Davin et al., 2011). In this research, the loss model was based on the assumptions and parameters of the Revitalised FSR/FEH rainfall-runoff method (Kjeldsen et al., 2005; Kjeldsen, 2007). The scope of usage of the ReFH model was to compute the infiltration loss and to produce the net rainfall hyetograph.

ReFHBDY unit of the Flood modeller suite interface consists of Catchment descriptor tab, Rainfall tab, and Models tab. Wortley Beck catchment descriptors, rainfall duration and loss model parameters were the essential inputs for this calculation.

1. Catchment descriptor tab

The catchment descriptors tab was filled with catchment descriptors data. The data was extracted from the Flood Estimation Handbook (FEH) CD-ROM Version 3 database (CEH, 2009) by using the easting and northing coordinates of Wortley Beck catchment.

Table 5.1 Catchment descriptors of WBC

Catchment Characteristics	WBC
Easting-Northing	X is 429750 and Y is 433000
Area (km^2)	63
URBEXT $_{2016}$	0.375
SAAR	761 mm
PROPWET	0.32 mm
DPLBAR	9.72 km
BFIHOST	0.394
DPSBAR	68.0 (m/km)
SPRHOST	34.42

Physical Characteristics of the catchment can be found at Table 5.1, where DPLBAR is mean drainage path length (km); DPSBAR is mean of all the inter-nodal slopes for the catchment (m/km); PROPWET is index of proportion of time that soils are wet; SAAR is Standard Period Average Annual Rainfall (mm); SPRHOST is Standard Percentage Runoff (%) derived using HOST classification; BFIHOST is Base flow index catchment descriptor URBEXT$_{2016}$ is a FEH index of urban and suburban land cover in 2016 (Houghton-Carr, 1999; Kjeldsen, 2007).

Depth-duration-frequency model catchment descriptor parameters are that c is -0.025, d1is 0.369, d2 is 0.365, d3 is 0.310, e is 0.300, and f is 2.380. The parameters of the Depth/Duration/Frequency (DDF) model were exported from FEH CD-ROM 3 (CEH, 2009), at 21:13:58 GMT on Tue 18-Aug-2015 for this research.

2. Rainfall tab

The rainfall duration of a rainfall event can be estimated from catchment descriptors and rainfall data. The rainfall duration of the Wortley Beck catchment was calculated by using ReFH rainfall-runoff model equation in this tab. One of the fundamental sections of a rainfall profile is the calculation of rainfall duration. Time to peak (Tp) and rainfall duration (D) were calculated (Equation 5.2 and 5.1) for Wortley Beck catchment by using the ungauged catchment equations of the ReFH rainfall-runoff method, which can be found in Equation 3.19 (Kjeldsen, 2007 document at page 19) and the value of the $URBEXT_{2016}$. Tp value was calculated as 2.24 hr., and D was calculated as 3.95 hr.

Equation 5.1 The Critical Storm Duration (h)

$$D = T_P(1 + \frac{SAAR}{1000})$$

Where in Equation 5.1: D is the Critical Storm Duration (h)

The storm duration (D) is calculated by using the response time of the catchment (time to peak, Tp) and the general wetness of the catchment (SAAR).

Equation 5.2 Time to Peak

$$Tp = 1.563 * PROPWET^{-1.09} * DPLBAR^{0.60} * (1 + URBEXT)^{-3.34} * DPSBAR^{-0.28}$$

Where in Equation 5.2: T_P is Time to Peak; SAAR is Standard Average Annual Rainfall (mm).

Storm Duration (hr.) was found as 3.9h for the Wortley Beck catchment.

Return period was selected for each design event. Storm area is the Wortley Beck catchment size. The estimation of the rainfall duration can be affected by the catchment topography, land use, size, and steepness. These parameters and values can be found in the Catchment descriptor tab.

3. Flood modeller suite REFHBDY Loss model

Loss model is applied to the total rainfall hyetograph to derive the net rainfall hyetograph by using a soil moisture accounting approach (Kjeldsen, 2007). A net rainfall hyetograph can display the direct runoff when simulating a flood event. In the Revitalised FSR/FEH rainfall-runoff method, the loss is calculated for each individual time step. In addition, this option is recommended for the design events. As the soil becomes increasingly wet during the rainfall, the loss decreases, and the runoff rate increases so the loss could change during this time. The loss model that is based on the uniform Probability Distributed Model (PDM) of Moore (1985) (Kjeldsen, 2007) and was used to remove the evaporation and infiltration rate of soil moisture storage, groundwater recharge and interception losses from gross rainfall. This allowed the net rainfall could be computed (Kjeldsen and Fry, 2006; Kjeldsen, 2007; Martinkova, 2013).

Loss model parameters are Cmax, Cini and α factor method. Cmax means maximum soil moisture capacity (mm). Cmax (Equation 5.4) can be estimated from Baseflow index BFIHOST and PROPWET of catchment descriptors, for ungauged catchments (Kjeldsen, 2007).

Cini means initial soil moisture content (mm) (Equation 5.5). Lastly, α factor method relies on the selected return period. It was estimated from ReFH Design Standard in the Flood modeller suite REFHBDY interface in this research.

A) Loss model for impermeable surfaces

Urbanised areas consist of the permeable and impermeable surfaces. The Wortley Beck catchment was divided into urban and rural areas according to the master map data. Urbanised areas were accepted as impermeable surfaces that could resist the infiltration of water. Whereas, in rural areas water could be more able to infiltrate into the soil and these permeable surfaces could have a tendency to be converted to direct runoff.

Calculating the loss model for impermeable surfaces is straightforward. ReFH boundary framework of the Flood modeller suite could define a fixed value of percentage runoff for impermeable areas. (Design rainfall event X loss factor of developed areas) formula gave net rainfall of the impermeable areas for each time step. Figure 5.6 displays the impermeable surfaces in the Wortley Beck catchment.

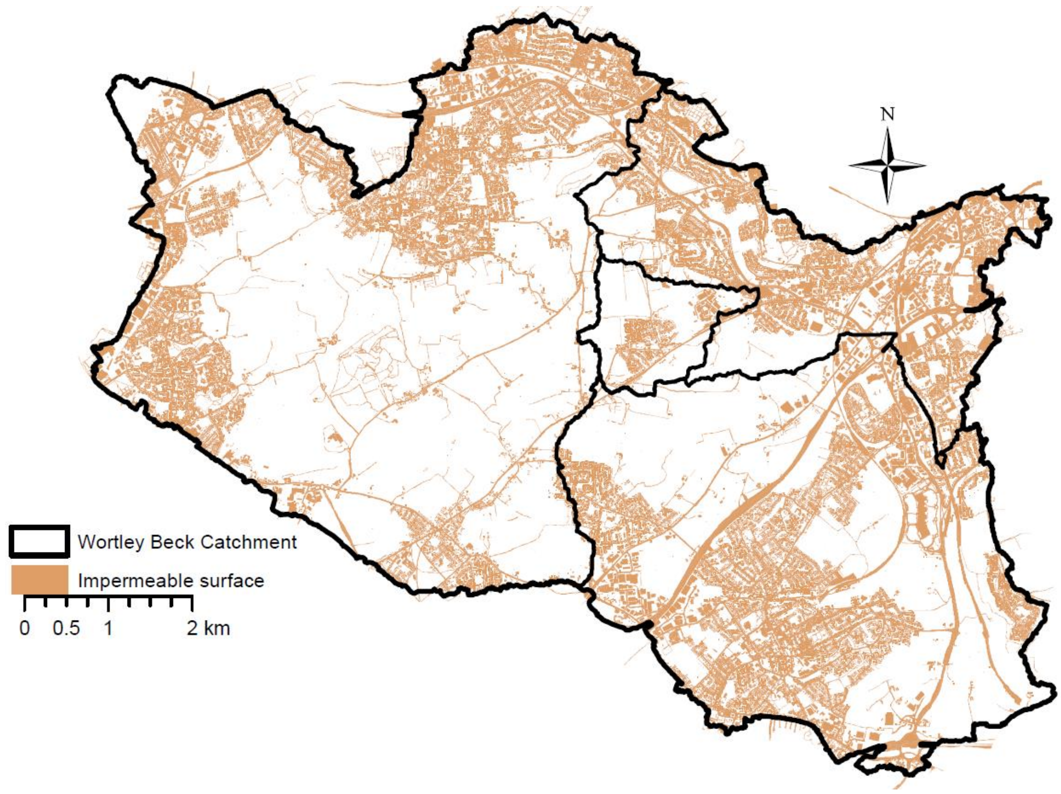

Figure 5.6 Impermeable surfaces in the Wortley Beck Catchment

In this research, direct surface runoff value was applied as 70% to the impermeable surfaces. The 70% is a good average value for built-up areas, and a mix of the city centre and more suburban land uses (Kjeldsen, 2007). The area of impermeable surfaces can be calculated from this formula (WBC AREA*URBEXT value).

B) Loss model for permeable surfaces

Permeable surfaces are undeveloped areas in the catchment. Undeveloped area was calculated from this formula (WBC AREA - (WBC AREA*URBEXT)). Hyetograph of the permeable surfaces was computed from the undeveloped tool in the flood modeller suite.

The loss model was applied to the permeable surfaces to generate net rainfall hyetograph. The formula (Design rainfall event X loss factor of undeveloped areas) gave net rainfall of the permeable areas for each time step. Loss factor of undeveloped areas can be applied by using percentage runoff value.

This value can be calculated from the maximum soil moisture capacity (Cmax), initial soil moisture content (Cini), and soil moisture correction factor (α_T) parameters.

B1.) The percentage runoff

During a rainfall event, the depth of water in each storage element is increased by rainfall and when rainfall exceeds the storage capacity, direct runoff (q_t) generates. The depth of water in each storage element increases by rainfall volume (P_t) at time (t). It is depleted by evaporation. The ratio q_t/P_t of rainfall transformed into the direct runoff is a measure of the percentage runoff. Equation 5.3 can be used to derive the percentage runoff (Kjeldsen, 2007).

Equation 5.3 The percentage runoff

$$\frac{q_t}{P_t} = \frac{C_{t-1}}{C_{max}} + \frac{P_t}{2C_{max}}$$

Where in Equation 5.3: C is soil moisture capacity at any time. It is constant for elements of the capacity greater than soil moisture storage (C_t) and it is at full capacity, for elements of the capacity smaller than C_t. Once C_t exceeds Cmax, the model assumes that 100% of the rainfall is converted into the runoff. Cmax is the maximum soil moisture capacity within the selected catchment (Stewart et al., 2003; Kjeldsen, et al., 2005; Kjeldsen and Fry, 2006).

B2.) The maximum soil moisture capacity (Cmax)

The model also requires an estimate for Cmax, which can also be obtained from catchment descriptors or defined by the user.

Equation 5.4 Cmax

$$\text{Cmax} = 596.7\text{x BFIHOST}^{0.95} \text{ x PROPWET}^{-0.24}$$

Where in Equation 5.4 (Kjeldsen, 2007): Cmax is the maximum soil moisture capacity within the selected catchment (mm). Cmax of Wortley Beck catchment value was found as 323.774 mm (Equation 5.4).

B3.) The initial soil moisture content (Cini)

Cini is estimated from the soil moisture content at the start of an event. Initial loss is applied to the rainfall amount before surface runoff occurs. It can include interception, surface wetting, and infiltration. Infiltration loss can change due to the surface properties. It is an estimation of the initial soil moisture content (Cini) at time zero. Cini is estimated on a seasonal basis (summer or winter) by using catchment descriptors (equations), or the user can define a value in millimetres. Cini was calculated from the catchment descriptor values in the ReFH rainfall-runoff model in this research (Kjeldsen, 2007).

Equation 5.5 The initial soil moisture content (Cini)

$$\mathrm{Cini, summer} = 0.5 \,\mathrm{x}\, \mathrm{C_{MAX}} \,\mathrm{x}(0.9 - 0.82\mathrm{xBFIHOST} - 0.43\,\mathrm{xPROPWET})$$

Where in Equation 5.5 (Kjeldsen, 2007): Cmax / 2 is the catchment average soil moisture capacity; BFIHOST is the base flow index derived from HOST classes and PROPWET is the proportion of time catchment soils are wet as described by Bayliss (1999). Cini value was found as 71.120 mm for the Wortley Beck catchment in this research (Equation5.5).

The season of storm profile was selected as summer, because the $\mathrm{URBEXT_{1990}}$ value of Wortley Beck catchment is greater than 0.125. Therefore, the 50% summer profile was used in the calculation (Kjeldsen, 2007).

B4.) Soil moisture correction factor (α_T)

The soil moisture correction factor (α_T) was necessary to calculate the loss factor of undeveloped areas. The correction factor (α_T) was set for the summer season in this calculation. The α_T correction factor from return period can be calculated by using Equation 5.6 (Kjeldsen, 2007) below,

Equation 5.6 Initial soil moisture correction factor

$$\alpha_{T,summer} = 1.444\, x\, \mathrm{T}^{-0.182}$$

Where in Equation 5.6: T is return period.

For return periods less than 5 years, initial soil moisture correction equals to 1 in both seasons. If return period (T) is bigger than 5 yr., this factor is applied to the calculation (Kjeldsen, 2007). Table 5.2 displays the correction factor (α_T) values for each design event for this research.

Table 5.2The α_T correction factor for each return periods

Design storm events (T)	**correction factor (α_T)**
1 in 5-year	1.0
1 in 15-year	0.886
1 in 30-year	0.776
1 in 50-year	0.710
1 in 100-year	0.630

5.2.5 Roughness

The surfaces of the catchment such as buildings, roads, car parks, and green areas were identified by using Master Map classification data. Manning`s n roughness values were taken from the Environment agency data and were applied for the feature of surfaces in the Wortley Beck catchment (Table 5.3).

Table 5.3 Land use materials

Manning's n values	**Feature of the surface**
0.1	Buildings, Building , Manmade
0.050	Land, General Surface, Multi Surface, Multiple,
0.050	Land, General Surface, Step, Manmade,
0.050	Land, General Surface, Natural, Manmade

0.100	Buildings, Glasshouse, Manmade
0.030	Water, Inland Water, Natural
0.050	Land, Landform, Natural
0.050	Land, Landform, Slope, Manmade
0.050	Land, Landform, Cliff, Natural
0.075	Land, Natural Environment, Orchard, Natural,
0.022	Roads Tracks And Paths, Path, Step, Manmade,
0.022	Roads Tracks And Paths, Path, Manmade,
0.080	Rail, Rail, Manmade,
0.022	Roads Tracks And Paths, Road /Track, Manmade,
0.040	Roads Tracks And Paths, Roadside, Manmade,
0.025	Structures, Structure, Manmade,
0.055	Structures, Structure, Manmade, Pylons
0.030	Water, Tidal Water, Foreshore, Natural,
0.050	Land, Landform, Cliff, Natural
0.075	Land, Natural Environment, Orchard, Natural,
0.030	Water, Tidal Water, Natural
0.050	Land, Unclassified, Unclassified,

5.2.6 Calibration process of the pluvial flood model

The aim of the calibration process was to assess the credibility of the computed results. The computed water level values were compared with the observed water level of the Pudsey stage gauge station. The measured water level at the Pudsey station was taken from the Environment Agency data. The predicted water level results were obtained by using TUFLOW 2D direct rainfall model for the same coordinate as the Pudsey stage gauge station.

A.) To compute water level

1. Measured stage water level data

Dates of the historical flood events were checked for the Wortley Beck catchment, then, water level values of the Pudsey station were analysed. There were water level data sets between 05/08/2011 and 21/01/2016.

The dates to use from the Pudsey stage gauge station were obtained by selecting high water values dates. The dates were listed below that,

06/07/2012, 24/09/2012, 25/11/2012, 15/11/2015, 12/12/2015, and 26/12/2015

After selection of the dates of the water level data from Pudsey stage station, rainfall data was analysed for these dates.

2. Measured gross rainfall data

The predicted water level results were produced by using measured rainfall data. Measured rainfall data was taken from Headingley, Knostrop and Heckmondwike rain gauge logger stations (Figure 5.9). Initially, historical flood events at the Wortley Beck catchment were investigated. Two criteria were used to select measured rainfall data. These were return period and the quality of the rainfall data. Firstly, return period of measured rainfall data was analysed, it should be enough to create flood flow for the model. Secondly, the continuity and consistency of the rainfall data were analysed.

These records have missing data due to natural damage or a fault with the rain gauge during the measurements. The data from these dates might not be enough for calibration. Therefore, the measured rainfall data of the 06/07/2012 and 24/09/2012 dates were found suitable for the validation process.

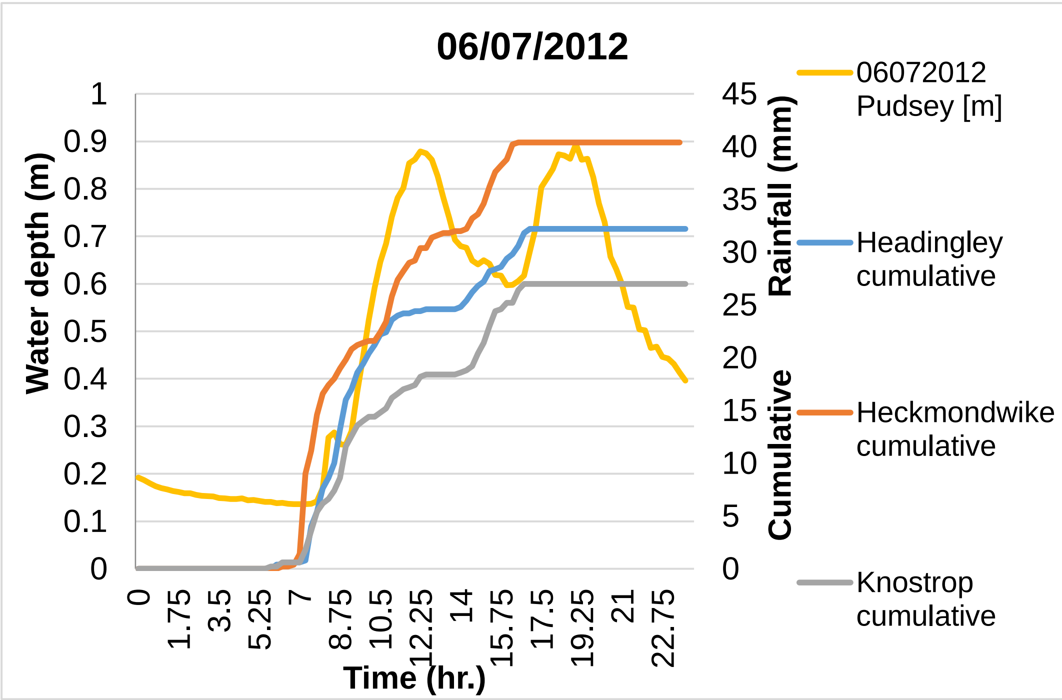

Figure 5.7 06/07/2012 event day

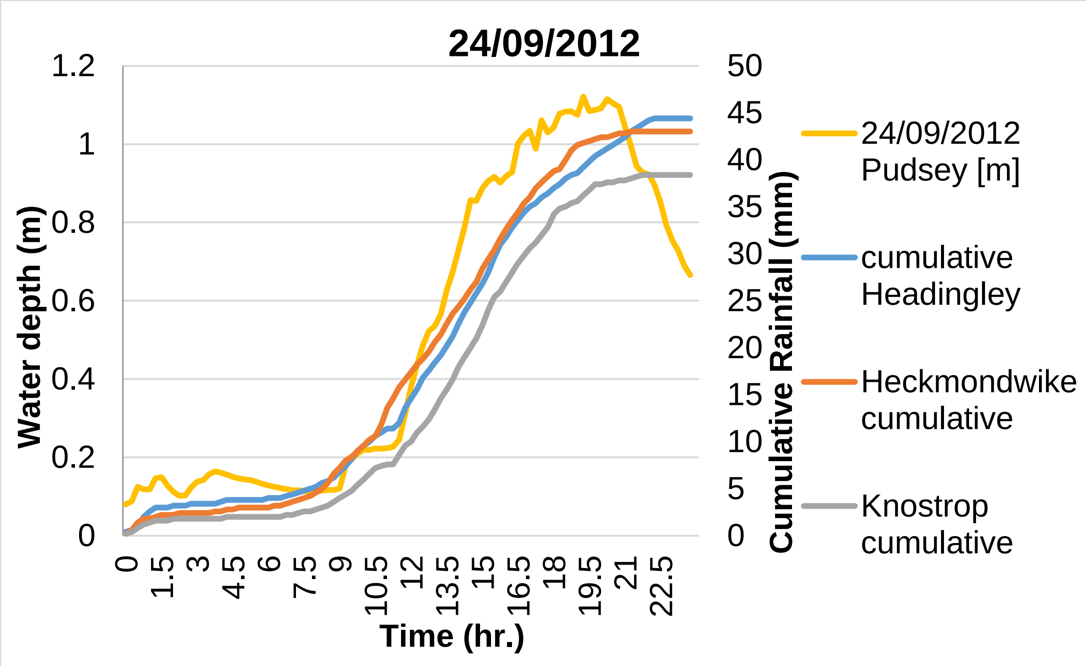

Figure 5.8 24/09/2012 event day

Figure 5.7 and 5.8 were created to observe the cumulative rainfall (mm) and water depth (m) values for event days.

5.2.6.1 Thiessen polygon method

Measured rainfall data was applied by using the mean precipitation approach in the model. Mean precipitation can be calculated from Thiessen polygon method (Tilford et al., 2003). Mean precipitation was computed by using gross rainfall data of the Headingley, Knostrop and Heckmondwike rain gauge logger stations.

The spatially averaged rainfall calculation was performed by using the below approach (Thiessen, 1911),

((Rainfall value of Headingley x area of Headingley rain gauge station) + (Rainfall value of Knostrop x area of Knostrop rain gauge station) + (Rainfall value of Heckmondwike x area of Heckmondwike rain gauge station)) / (The area of Wortley Beck catchment)

The areas of the rain gauge stations were calculated by using GIS tool and the results are displayed below (Figure 5.9). The areas for the rain gauge stations are 26 km^2 for Headingley, 18 km^2 for Knostrop and 17 km^2 for Heckmondwike in Figure 5.9.

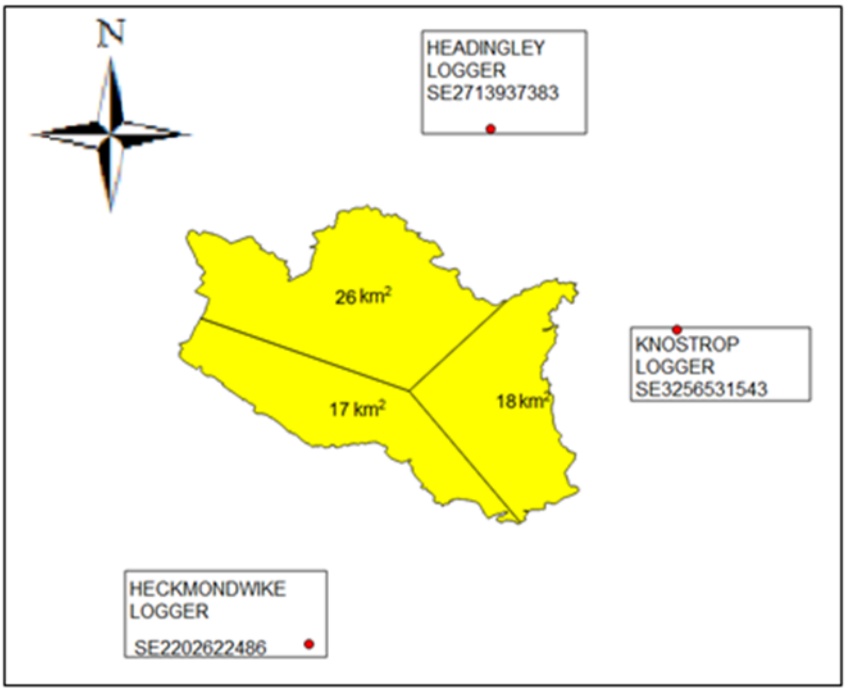

Figure 5.9 Thiessen method

Figure 5.9 indicates locations of rain gauges and denotes the area of each polygon.

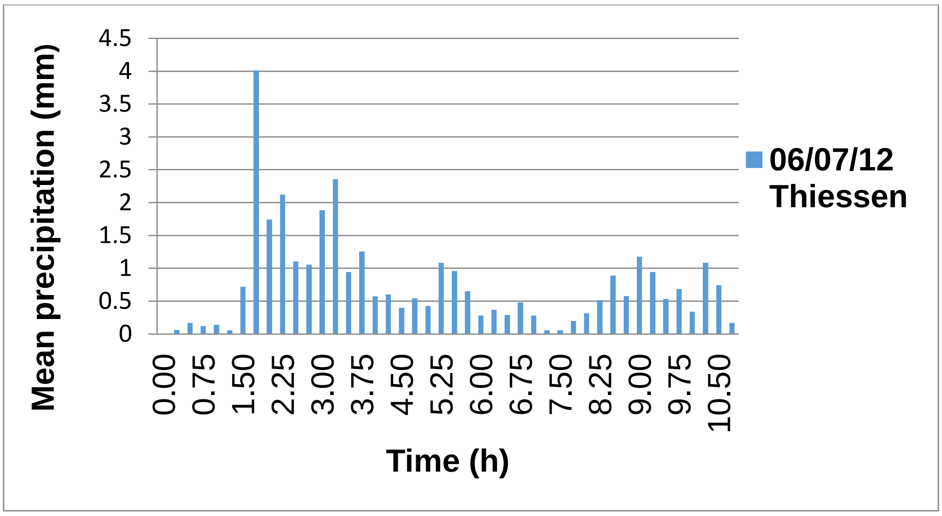

Figure 5.10 Gross rainfall of the 06/07/2012 event

Figure 5.10 displays the gross rainfall data of the 06/07/2012 date from Thiessen polygon method. Rainfall duration is 11 hours of the 06/07/2012 event.

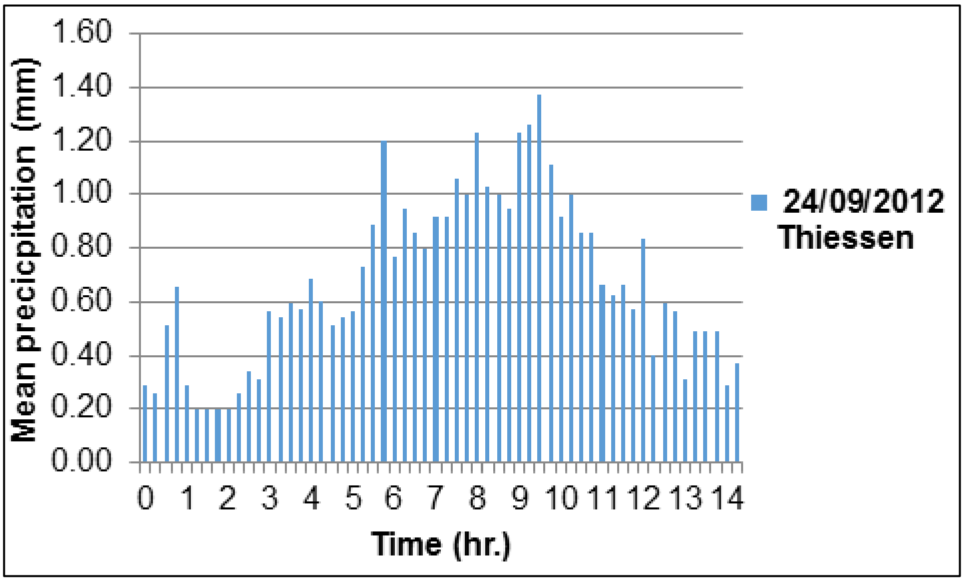

Figure 5.11 Gross rainfall of the 24/09/2012 event

Figure 5.11 displays the gross rainfall data of the 24/09/2012 date from Thiessen polygon method. Rainfall duration is 14.25 hours of 24/09/2012 event.

3. Net rainfall data was calculated from the gross rainfall data

After mean precipitation was calculated by using Thiessen polygon method, net rainfall hyetograph was computed for impermeable and permeable surfaces by using the ReFH boundary unit of the Flood modeller suite.

4. Net rainfall data was entered to the 2D Hydrodynamic model to compute water level

The net rainfall hyetograph was entered into the TUFLOW 2D direct rainfall model to produce water level. The computed water level data was used to compare with the measured water level data of the Pudsey gauge station. TUFLOW 2D surface flood was simulated by using 5 m cell resolution. Urban permeable and impermeable surfaces data based on the year of 2016 were used.

5. The computed water level

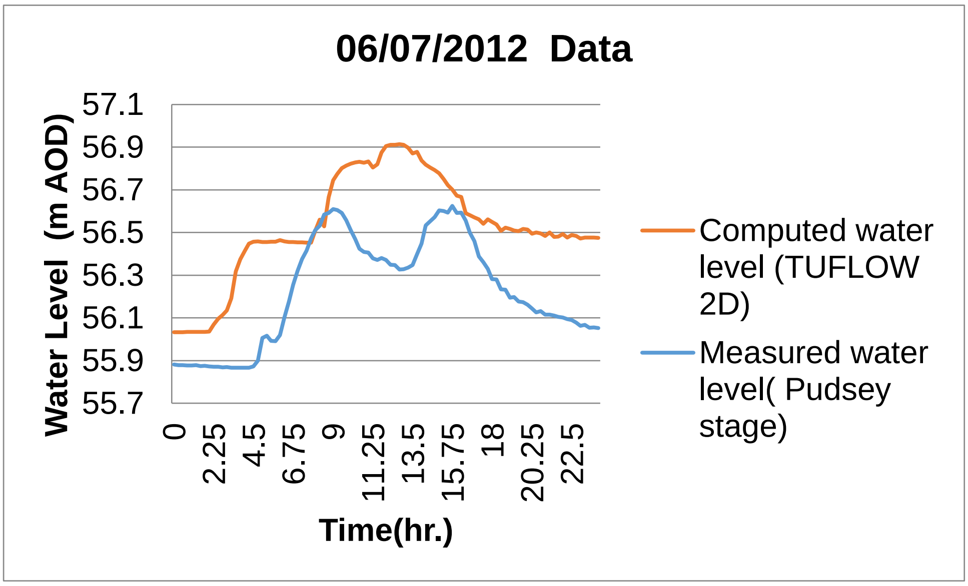

Figure 5.12 Water level from rainfall data of 06/07/2012

Figure 5.12 displays the computed water level of the 06/07/2012 date from Thiessen polygon method and measured water level values from Pudsey stage gauge station of 06/07/2012 date.

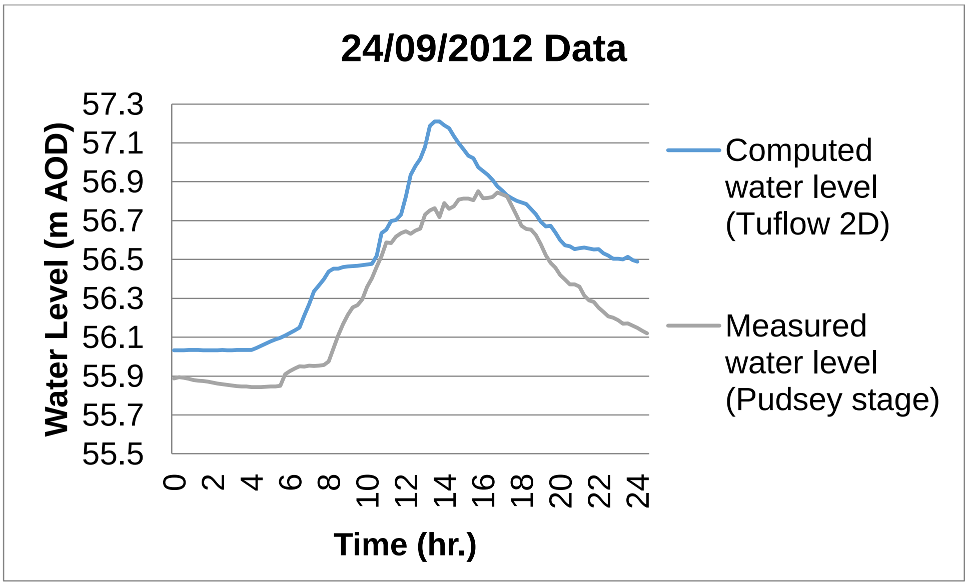

Figure 5.13 Water level from rainfall data of 24/09/2012

Figure 5.13 displays the computed water level of the 24/09/2012 date from Thiessen polygon method and measured water level values from Pudsey stage gauge station of 24/09/2012 date.

It can be said that the predicted water levels are higher than the water levels of the Pudsey stage station. The reasons for the differences between measured and computed results could be due to the quality of rainfall data. Rainfall data for some days was either missing or suspected. In addition to this, rainfall cannot be uniform over the entire catchment. The lack of adding the continuous loss in the model could cause this result. Thiessen polygon method and simplified surface features from the master map data cannot capture the influence of topography on the rainfall event. Lastly, the behaviour of computed and measured water level is similar, only computed water level value is higher than measured water level. The reason for this difference could be the model resolution. Using smaller than 5 m cell size of model resolution can make the computed water level values lower so they can be closer.

5.2.7 Estimation of the flood frequency for Farnley Beck sub-catchment

To determine the relationship of return period between the rainfall events and flood events, flood frequency analysis was performed in this research. The peak flow value of the discharge at the outfall point of the Farnley Beck sub-catchment was computed by using 2D TUFLOW direct rainfall modelling approach (Figure 5.14).

The statistical flood estimation (pooled group) method was used to estimate the return periods of peak flow values. The pooled group was obtained from WINFAB FEH CD version 3.0 according to the catchment descriptor parameters of the Farnley Beck sub-catchment.

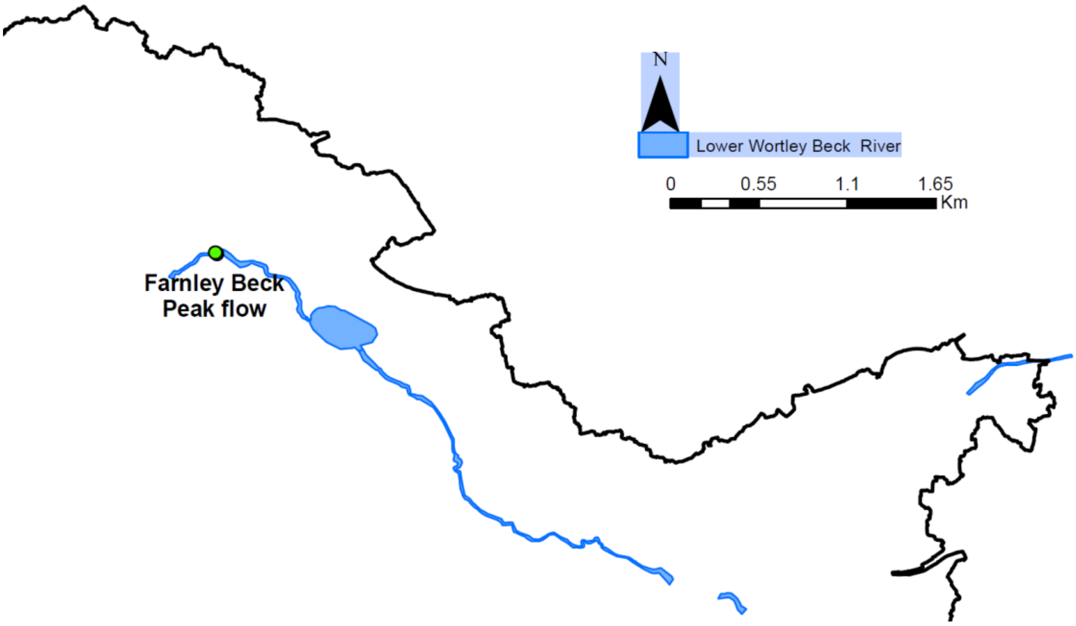

Figure 5.14 Peak flow discharge point

The location of the peak flow discharge at the Lower Wortley Beck can be found in the Figure 5.14.

The FEH statistical procedure for flood frequency estimation was applied by using WINFAP-FEH 3™ software. WINFAP-FEH 3™ software package was released on 9 September 2009 by Wallingford HydroSolutions Ltd (WHS, 2009). The WINFAP-FEH 3™ software could create flood frequency curves for flood estimation so that a relationship between the peak flow and the expected frequency of occurrence could be defined (WHS, 2009).

1. Estimating $QMED_{rural}$ from catchment descriptors

$QMED_{rural}$ can be estimated by using the catchment descriptor method when the subject catchment is ungauged or had a length of the AM or POT flood data is lower than two years (WHS, 2009). Therefore, Kjeldsen et al. (2008) `s $QMED_{rural}$ catchment descriptor was used (Equation 5.7) in this research.

Equation 5.7 $QMED_{rural}$ catchment descriptor

$$\mathrm{QMEDrural} = 8.3062\mathrm{AREA}^{0.8510}\, 0.1536^{\left(\frac{1000}{\mathrm{SAAR}}\right)} \mathrm{FARL}^{3.4451}\, 0.0460^{\mathrm{BFIHOST}^2}$$

Where in Equation 5.7: AREA is catchment area (km^2); SAAR is standard average annual rainfall (mm); BFIHOST is hydrological soil properties and FARL is index of flood attenuation based on upstream reservoirs and lakes (Kjeldsen et al., 2008; WHS, 2009; Kjeldsen and Jones, 2010). These catchment descriptors can be found at FEH CD-ROM 3 software.

Farnley Beck catchment descriptors for the calculation $Qmed_{rural}$ were that AREA was 29.67 km^2, SAAR value was 799 (mm), FARL value was 1.0, and the BFIHOST value was 0.449. $Qmed_{rural}$ value was calculated as a 7.66 m^3/s by using catchment descriptor (Equation 5.7).

2. Defining a pooling group

While gauged catchments of pooled group were selected, the pooled group was generated by using WINFAP-FEH_v4.1 data at the Centre of Ecology and Hydrology (CEH) web page (http://nrfa.ceh.ac.uk/winfap-feh-files).

3. Urbanisation calculation

$URBEXT_{2000}$ value can be updated for the year of the present. Equation 5.8 by Bayliss et al. (2006) was used to apply the urbanisation adjustment to the $URBEXT_{2000}$.

Equation 5.8 Urban Extension Factor (UEF)

$$\mathrm{UEF} = 0.7851 + (0.2124 * \mathrm{ATAN}\,((\mathrm{YEAR} - 1967.5)/20.32))$$

To estimate flood frequency of Farnley Beck sub-catchment, a statistical procedure was applied by using $URBEXT_{2000}$. According to the URBEXT $_{2000}$ value, that is 0.219, the urban extent of the Farnley Beck sub-catchment in the 2016 year was assumed by using urban extent factor equation (Equation 5.8).

During this research, urbanisation of Wortley Beck catchment was assumed as a 2016 year so the urban adjustment was applied to the $Qmed_{rural}$. So, it was calculated as a 0.226 m^3/s.

4. The urban adjustment methods

If the URBEXT $_{2000}$ value of the subject site is bigger than 0.03, additional procedures are recommended to apply to produce a growth curve because urbanisation has a significant impact on flooding.

Urban adjustment Equation 5.9 was applied to the $QMED_{rural}$ to assess the impact of urbanisation on the flood frequency curve (WHS, 2009).

Equation 5.9 The urban adjustment

$$\mathrm{QMED} = \mathrm{UAF}\ \mathrm{QMED}_{\mathrm{rural}}$$

Where in Equation 5.9: $QMED_{rural}$ is multiplied by the Urban Adjustment Factor (UAF) (WHS, 2009).

UAF is calculated by using Equation 5.10:

Next, by using this value in urban adjustment factor, Equation 5.10 (Robson and Reed, 1999) Qmed was calculated as 9.894 m^3/s value.

Equation 5.10 The Urban Adjustment Factor (UAF)

$$\mathrm{UAF} = (1 + \mathrm{URBEXT}_{2000})^{0.37}\mathrm{PRUAF}^{2.16}$$

Where in Equation 5.10: URBEXT $_{2000}$ is Urban extent value of the 2000 year; PRUAF is the percentage runoff urban adjustment factor and was defined by Kjeldsen (2010) (Equation 5.11).

Equation 5.11 the percentage runoff urban adjustment factor

$$\mathrm{PRUAF} = 1 + 0.47\mathrm{URBEXT}_{2000}\left(\frac{\mathrm{BFIHOST}}{1 - \mathrm{BFIHOST}}\right)$$

5. Estimating QMED by data transfer

In addition to this, because of Qmed was calculated from catchment descriptor equation, it was adjusted by using donor catchment. The closest gauged catchment was used for this aim, and it was selected by using WINFAB FEH CD version 3. The basic transfer process for adjustment was applied by using Kjeldsen et al., (2008) `s data transfer equation (Equation 5.12).

Equation 5.12 The transfer equation

$$\mathrm{QMED}_{\mathrm{s,adj}} = \mathrm{QMED}_{\mathrm{s,cds}}\left(\frac{\mathrm{QMED}_{\mathrm{g,obs}}}{\mathrm{QMED}_{\mathrm{g,cds}}}\right)^{\mathrm{a}_{\mathrm{sg}}}$$

$$\mathrm{a}_{\mathrm{sg}} = 0.4598\exp(-0.02\mathrm{d}_{\mathrm{sg}}) + (1 - 0.4598)\exp(-0.4785\mathrm{d}_{\mathrm{sg}})$$

The steps of the procedure of the data transfer

1. A donor site is selected

2. QMED ($QMED_{g,obs}$) of the donor site is derived.

$QMED_{obs}$ is the observed QMED value and calculated from the AM data.

3. QMED value is calculated from catchment descriptors for both the subject site and donor site, $QMED_{s,cds}$ and $QMED_{g,cds}$, respectively.

$QMED_{s,adj}$ is the adjusted value of QMED for the subject site

4. d_{sg} is the geographical distance (km) between the centroid of the subject site and the centroid of the donor site (Kjeldsen et al., 2008; WHS, 2009).

The $QMED_{s,adj}$ value was calculated as a 10.18 m^3/s.

6. Estimating an appropriate flood growth curve

A flood growth curve (z_T) was constructed by using the pooling-group data to derive a flood frequency curve. The flood frequency curve can be obtained by multiplying with the z_T by QMED (Kjeldsen et al., 2008; WHS, 2009).

Equation 5.13 Estimation of the peak flow for return interval

$$Q_T = QMEDz_T$$

Where in Equation 5.13: Q_T is the peak flow for a return interval (T)

Estimation of peak flow for the return interval was calculated by using Equation 5.13. A flood growth curve was created by fitting the Generalised Logistic (GL) distribution. Finally, flood frequency was computed by using this value.

A given return period of a rainfall event is used as an input to a rainfall-runoff model. The return period of the rainfall event is accepted as the same as the return period of computed peak discharge in the ungauged catchment (Packman and Kidd, 1980; Bradley and Potter, 1992). However, return period of the rainfall event could be different from the return period of the flood event in nature (Linsley et al., 1988). The correlation between rainfall return period (T_R) and flood return period (T_Q) is an important parameter to assess flood frequency and to manage flood risk. Nevertheless, this relationship could not be completely identified (Viglione and Blöschl, 2009).

It is not a straightforward process. Rainfall intensity, rainfall duration, temporal and spatial storm patterns, and antecedent soil moisture are required in detail to assess this relationship (Viglione and Blöschl, 2009).

5.3 Pluvial flood modelling results

In this section, the results of the TUFLOW 2D direct rainfall model were displayed. These outcomes can be used for the assessment of the pluvial flood risk in Wortley Beck Catchment.

The estimated hyetograph was the main input data of the direct rainfall model and each hyetograph can be seen in between Figure 5.15 and 5.20. The storm duration of Wortley Beck catchment was calculated as 3.95 hr., by the Revitalised Flood Hydrograph (ReFH) model. Net rainfall hyetograph of the impermeable areas, permeable areas, and total rainfall (mm) were obtained for each design event.

5.3.1 The estimated hyetographs

Storm hyetograph was generated for the following events

1. Pluvial flood events were designed by estimating hyetographs for various return periods, covering the 1 in 5-year, 1 in 15-year, 1 in 30-year, 1 in 50-year, and 1 in 100-year event (from Figure 5.15 to Figure 5.19).

2. Pluvial flood events were designed for different rainfall durations (hr.) as well, covering the 0.5hr., 1hr., and 6hr. rainfall durations of the 1 in 100-year event (Figure 5.20).

Figures display the rainfall depth (mm) for time durations (hr.). The rainfall depth values display total rainfall (gross), impermeable surfaces (Imp) and permeable surfaces (Perm), lastly, cumulative gross rainfall depth values. These figures can be used to assess the input values for the modelling approach.

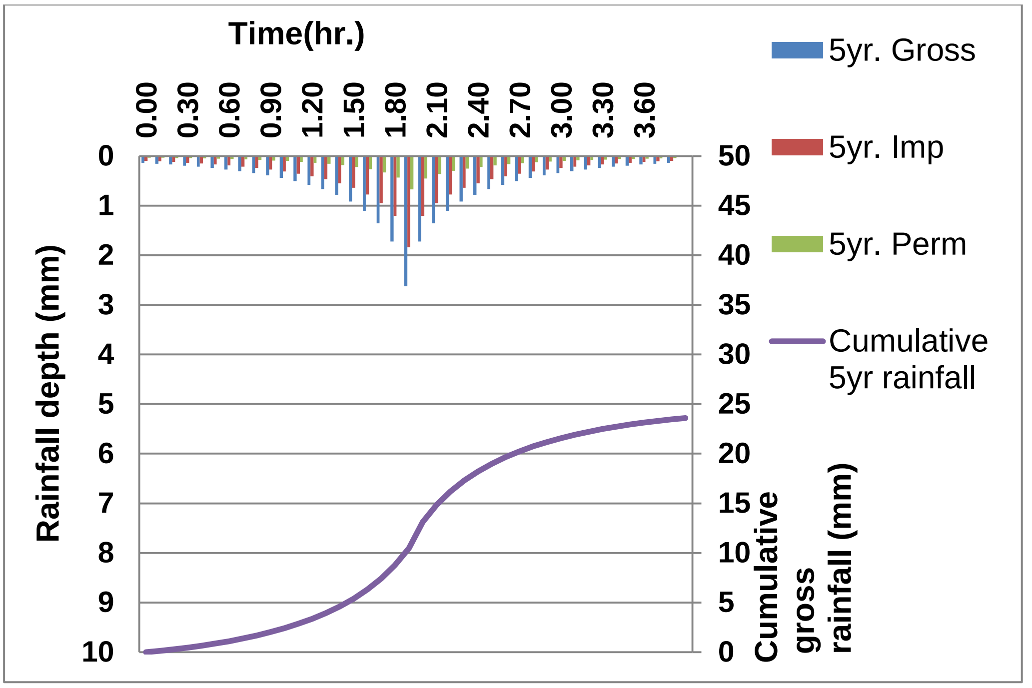

Figure 5.15 Estimated hyetographs for the 1 in 5-year event

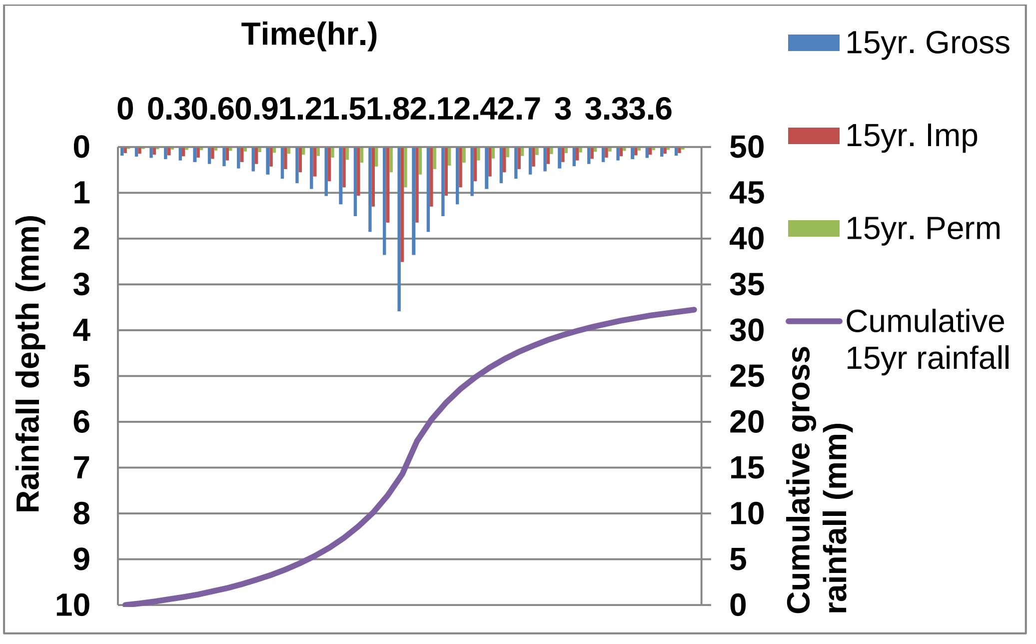

Figure 5.16 Estimated hyetographs for the 1 in 15-year event

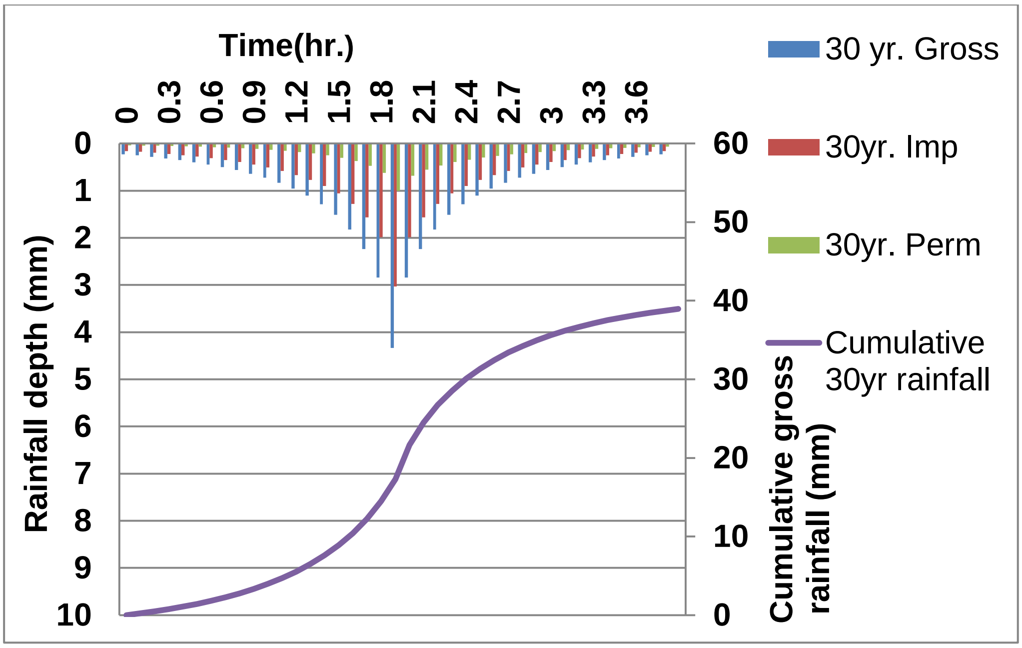

Figure 5.17 Estimated hyetographs for the 1 in 30-year event

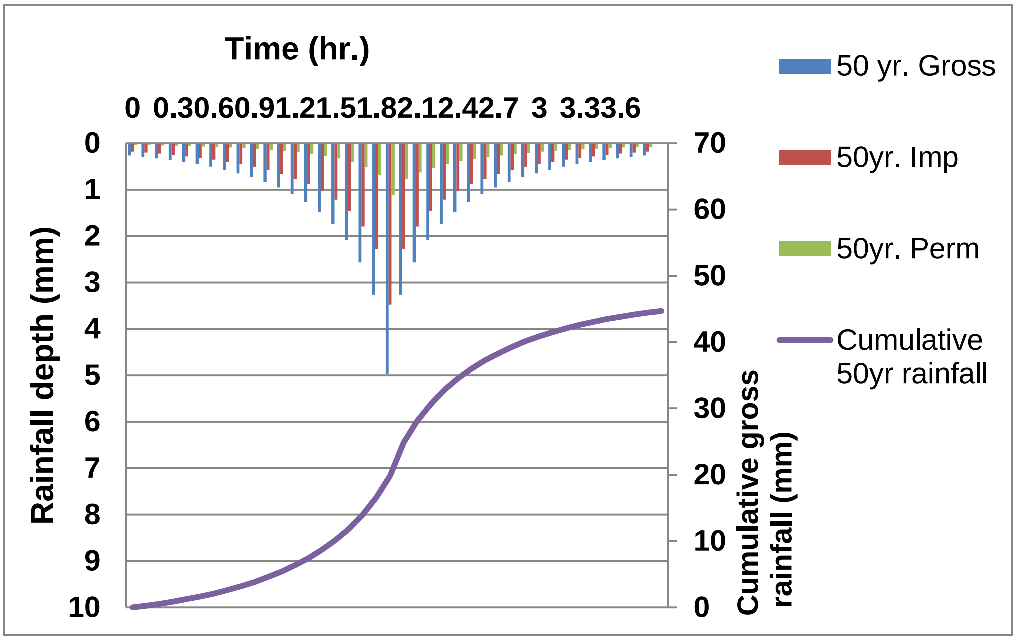

Figure 5.18 Estimated hyetographs for the 1 in 50-year event

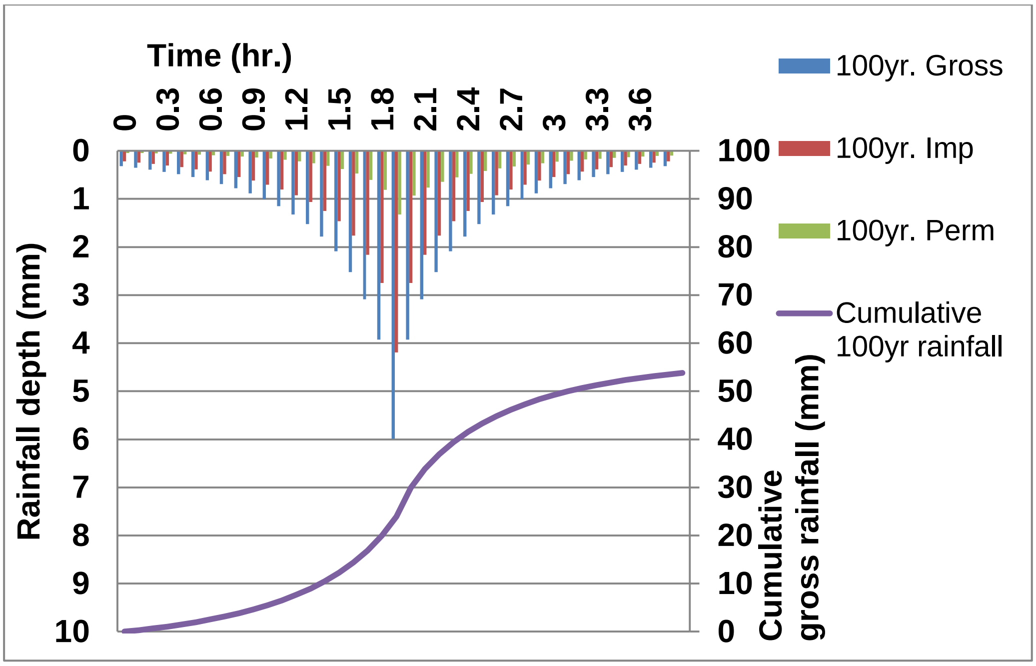

Figure 5.19 Estimated hyetographs for the 1 in 100-year event

While the frequency of the rainfall event is greater, rainfall depth values of the rainfall events become greater.

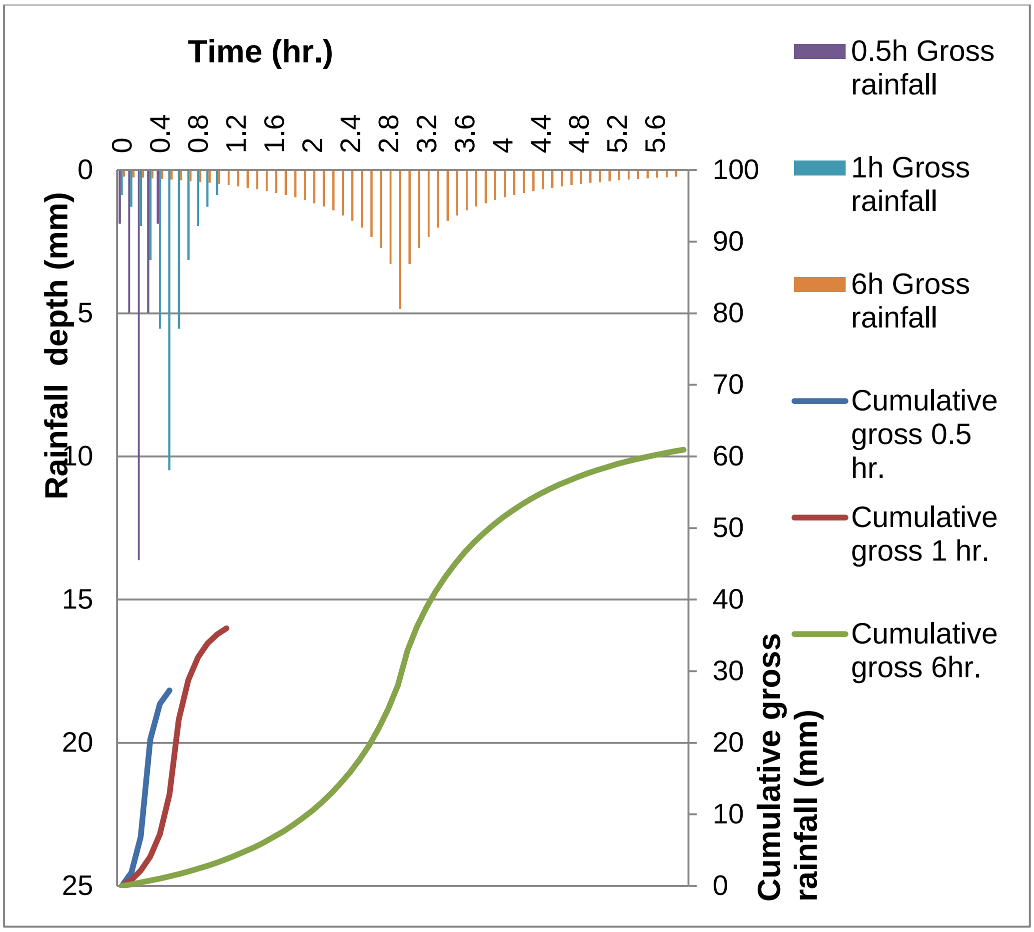

Figure 5.20 Cumulative gross rainfall events for the1 in 100-year event for 0.5/1/6 hr., rainfall durations

Longer rainfall duration (6 hr.) can have lower peak rainfall depth (mm) but have greater cumulative gross rainfall depth (mm) in comparison to short duration of rainfall events (0.5/1hr.) within the same return period (1 in 100-year event) (Figure 5.20).

After estimating the rainfall events, the rainfall data of impermeable and permeable surfaces was entered into the 2D hydrodynamic model directly, and probabilistic flood inundation maps were obtained.

5.3.2 Pluvial flood inundation maps

The pluvial flood inundation maps of the Wortley Beck catchment (WBC) were produced from each estimated rainfall data. This was to assess the impact of return period of rainfall event and the impact of rainfall duration on the pluvial flooding. Pluvial flood extent maps were produced by using TUFLOW 2D hydrodynamic software link GIS tool.

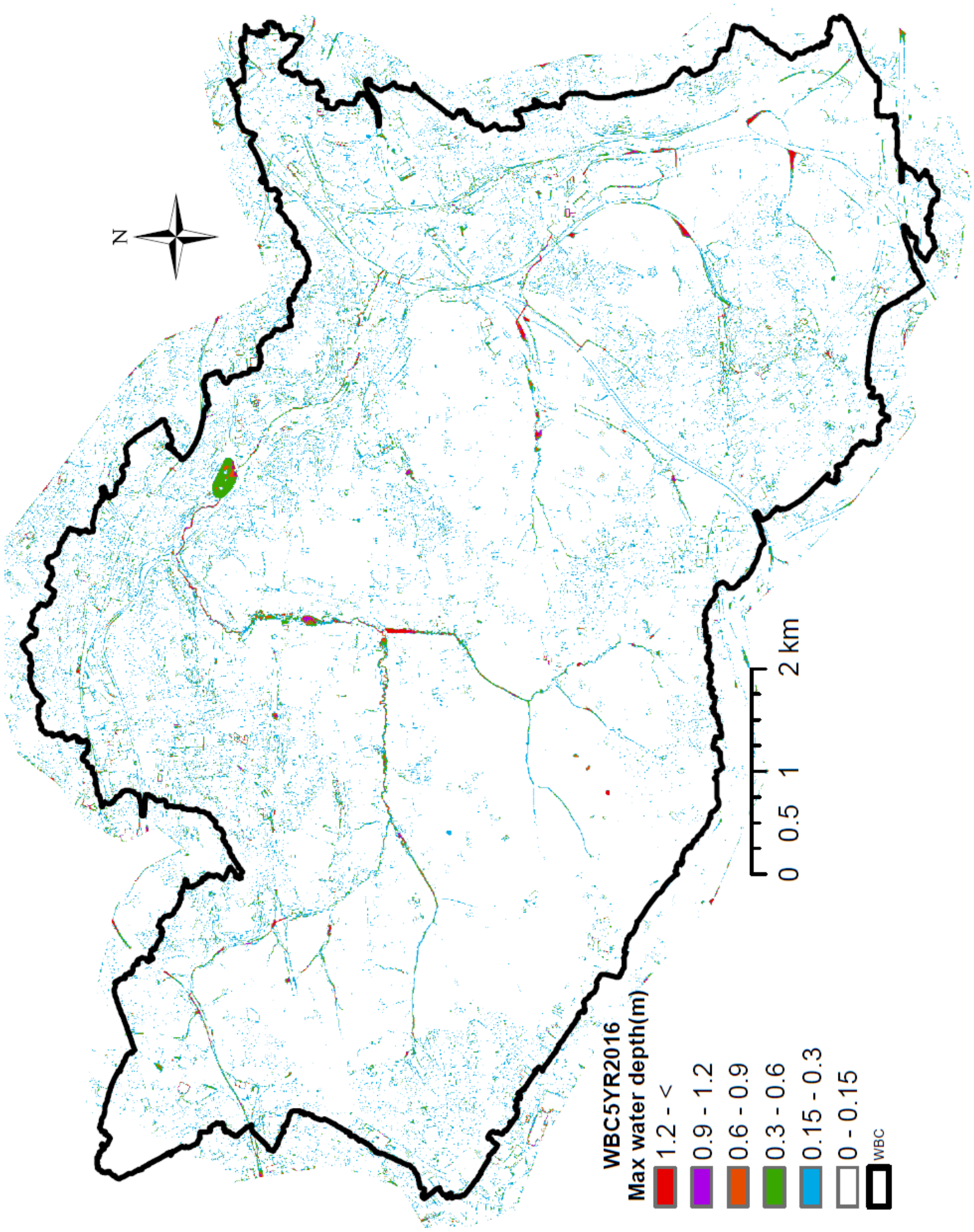

Figure 5.21 Rainfall event for the 1 in 5-year event

Figure 5.21 displays surface flood inundation areas in the Wortley Beck catchment for the 1 in 5-year rainfall event.

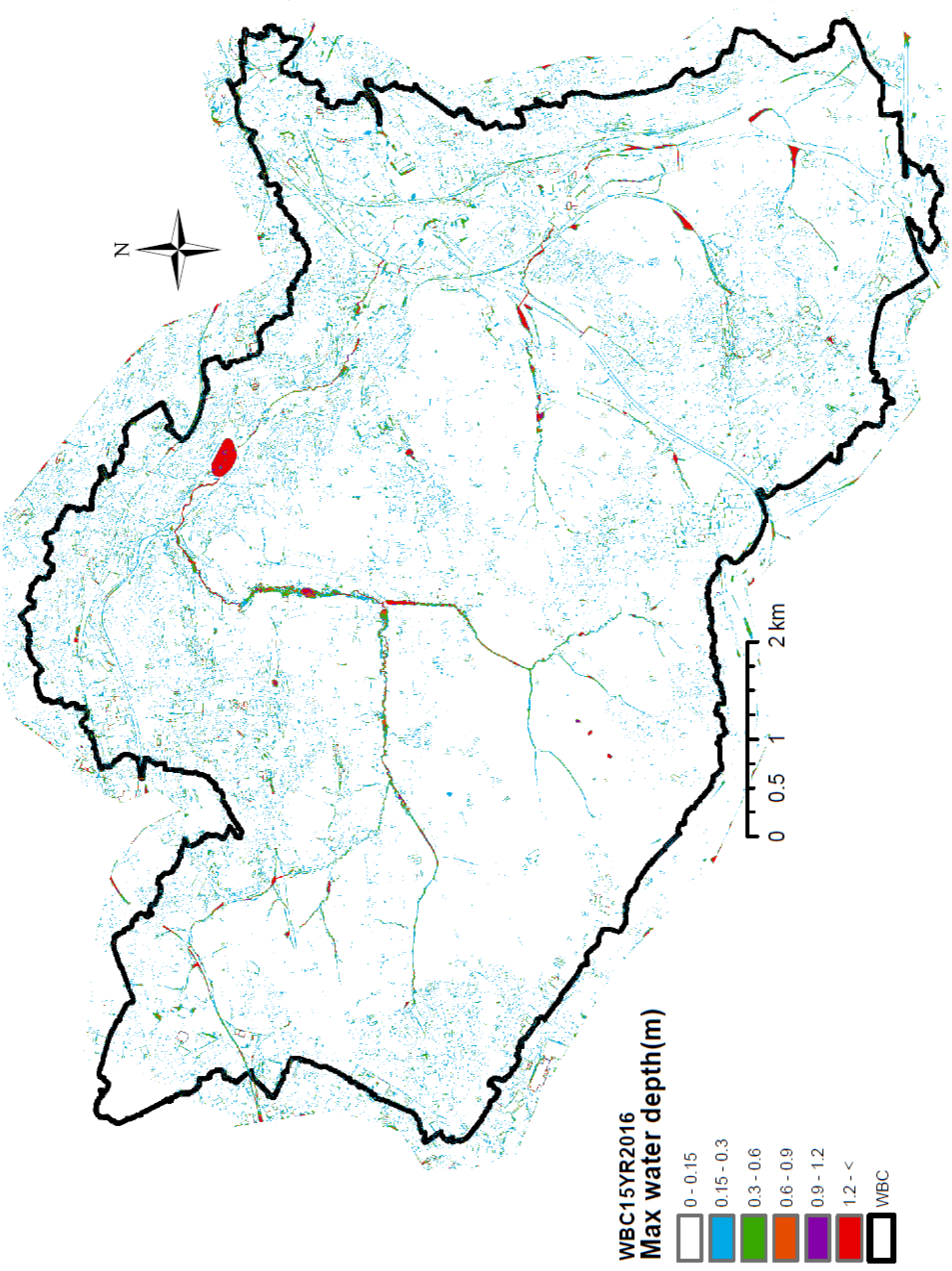

Figure 5.22 Rainfall event for the 1 in 15-year event

Figure 5.22 displays surface flood inundation areas in the Wortley Beck catchment for the 1 in 15-year rainfall event.

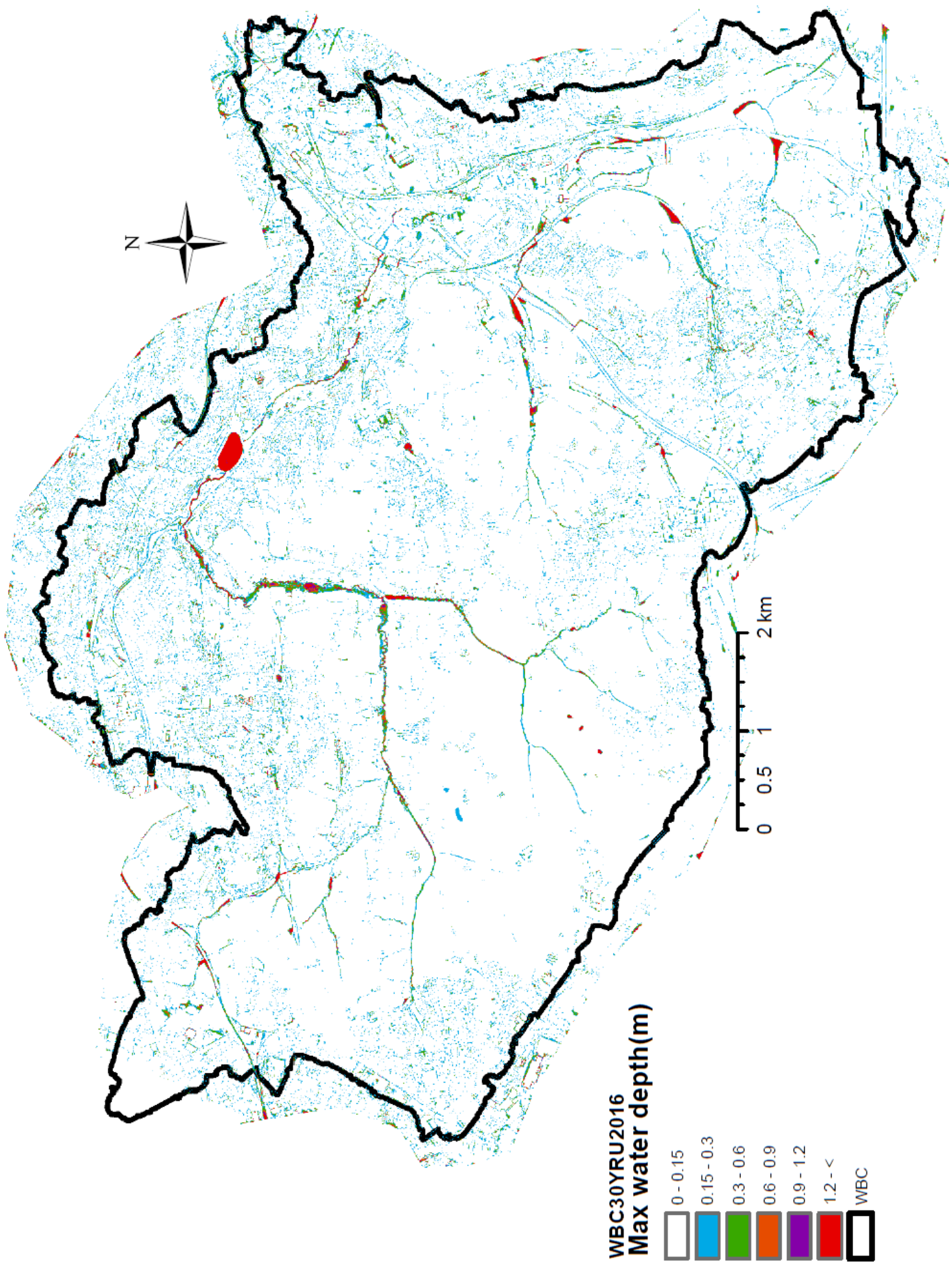

Figure 5.23 Rainfall event for the 1 in 30-year event

Figure 5.23 displays surface flood inundation areas in the Wortley Beck catchment for the 1 in 30-year rainfall event.

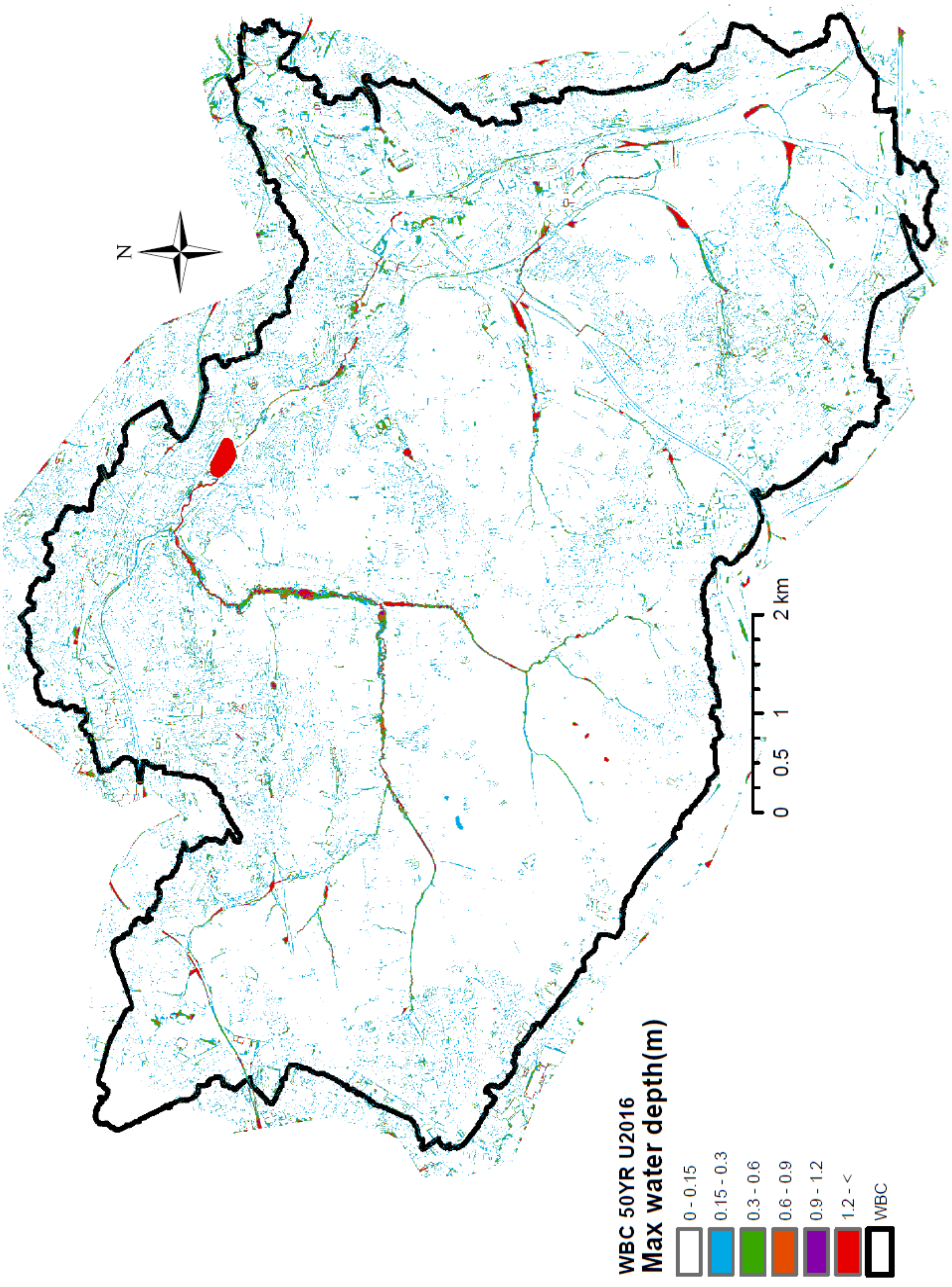

Figure 5.24 Rainfall event for the 1 in 50-year event

Figure 5.24 displays surface flood inundation areas in the Wortley Beck catchment for the 1 in 50-year rainfall event.

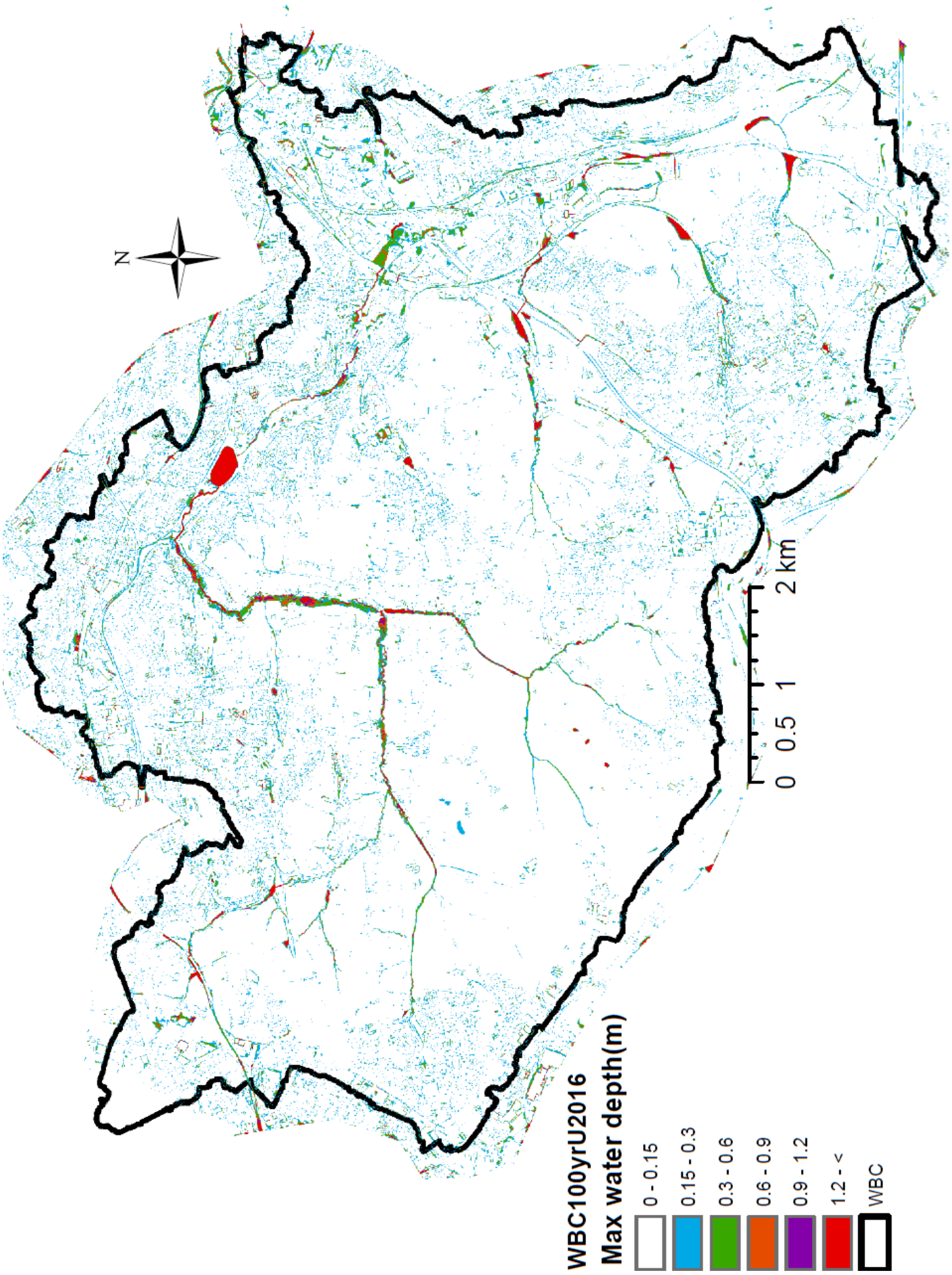

Figure 5.25 Rainfall event for the 1 in 100-year event

Figure 5.25 displays surface flood inundation areas in the Wortley Beck catchment for the 1 in 100-year rainfall event.

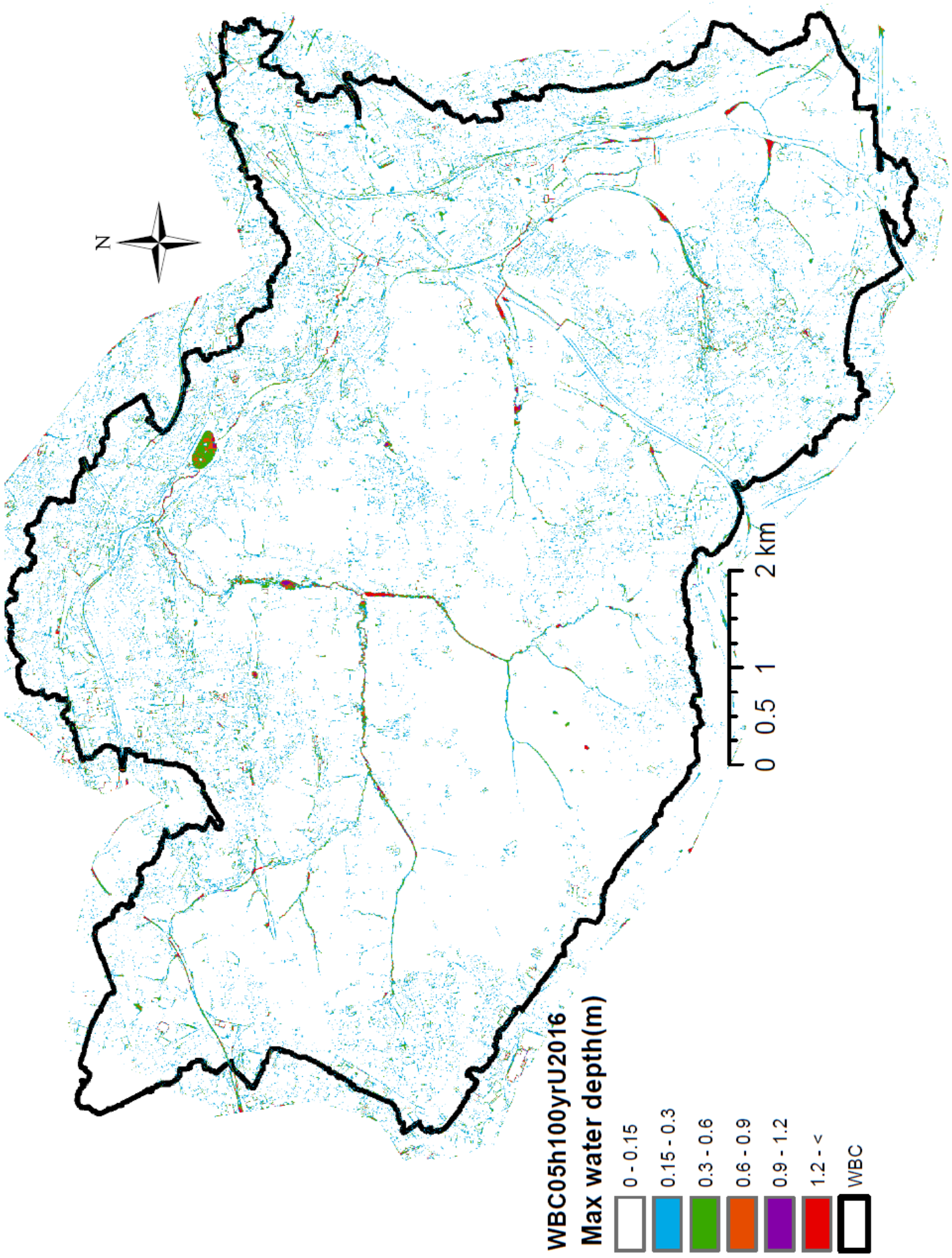

Figure 5.26 Rainfall event for the 0.5 hour duration of the 1 in 100-year event

Figure 5.26 displays surface flood inundation areas in the Wortley Beck catchment for the 30 minutes of 1 in 100-year rainfall event.

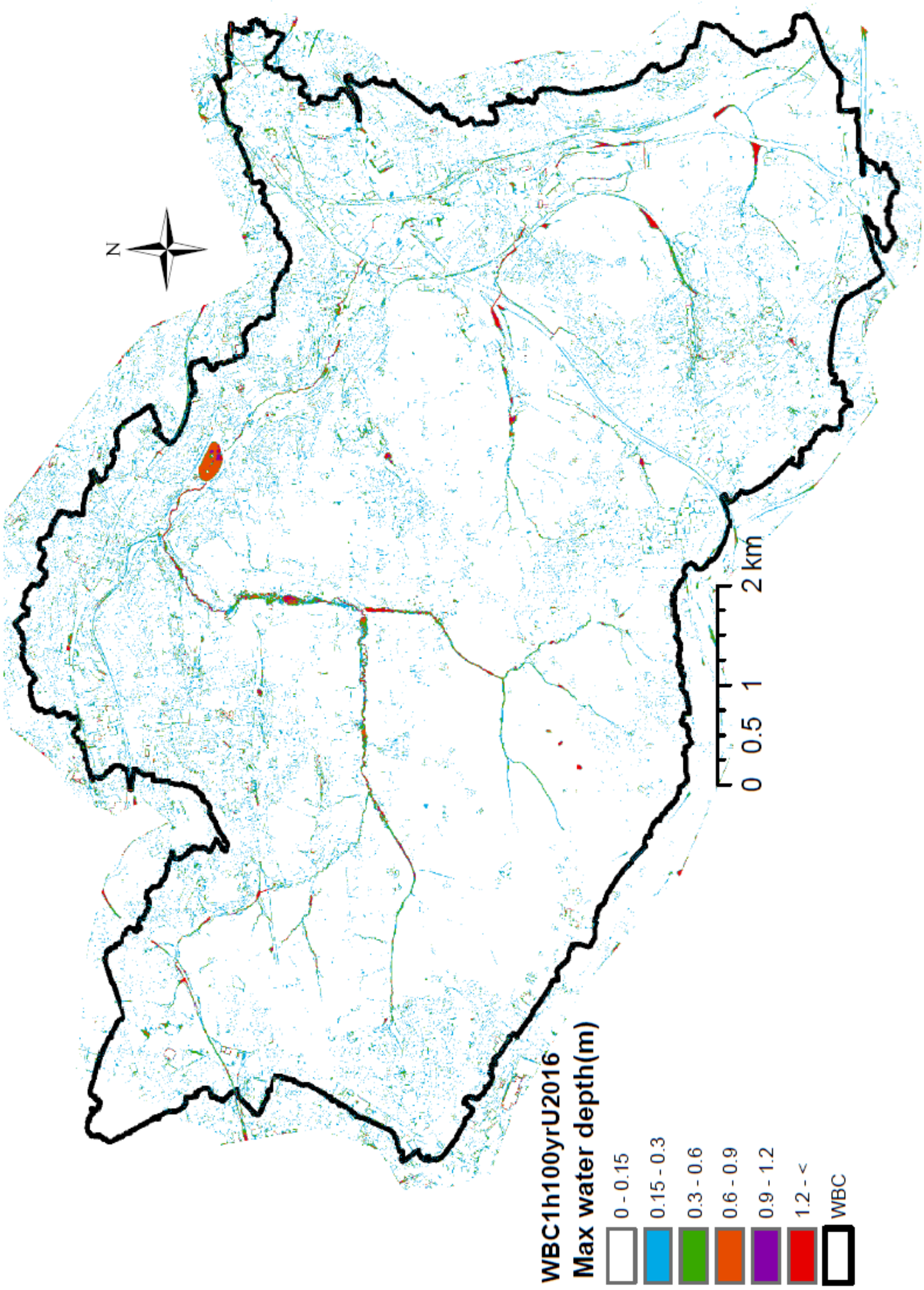

Figure 5.27 Rainfall event for the 1 hour duration of the 1 in 100-year event

Figure 5.27 displays surface flood inundation areas in the Wortley Beck catchment for the 1-hour of 1 in 100-year rainfall event.

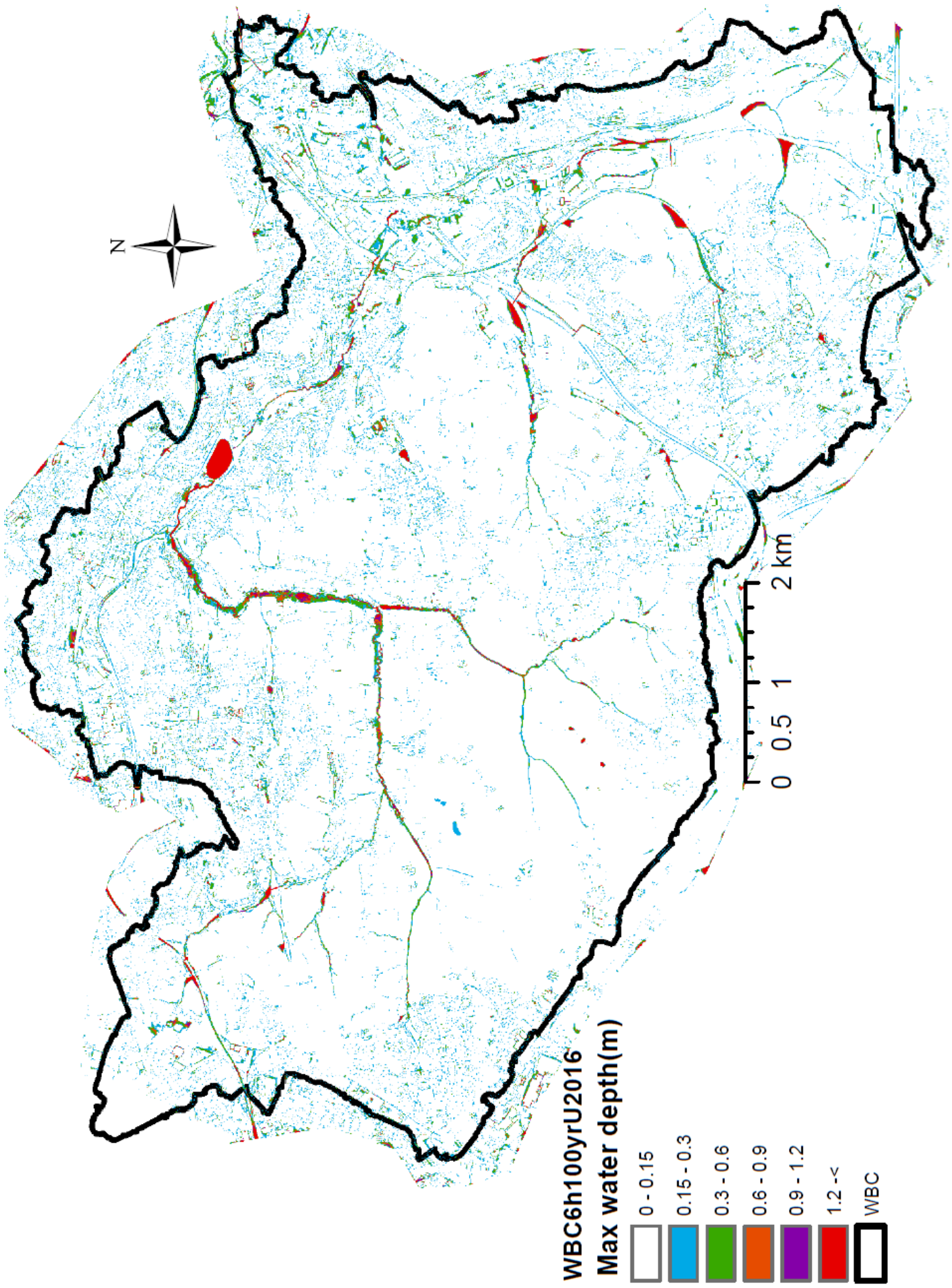

Figure 5.28 Rainfall event for the 6hour duration of the 1 in 100-year event

Figure 5.28 displays surface flood inundation areas in the Wortley Beck catchment for the 6-hour of 1 in 100-year rainfall event.

5.3.3 Water depth results

From design rainfall events, the figures and probabilistic flood inundation maps were produced

1. To assess the impact of return period of rainfall event on the surface flood water depth.

2. To assess the impact of rainfall duration of rainfall event on the surface flood water depth.

A.) Water depth percentages and Rainfall return periods

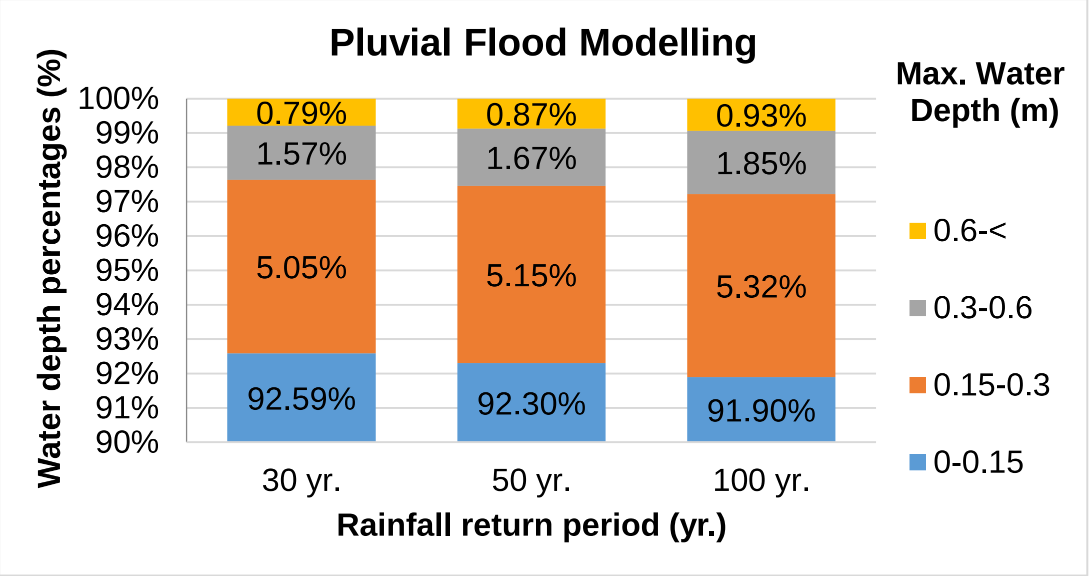

Figure 5.29 The percentages of the water depth values for rainfall return periods (30 yr., 50 yr., and 100 yr.)

Figure 5.29 displays the percentages of water depth values in the flood inundation areas of rainfall events for the 1 in 30-year, 1 in 50-year, and 1 in 100-year event of 4hr. rainfall duration. Water depth values were scaled between 0.15 m and 0.6 m above.

B.) Water depth percentages and Rainfall duration

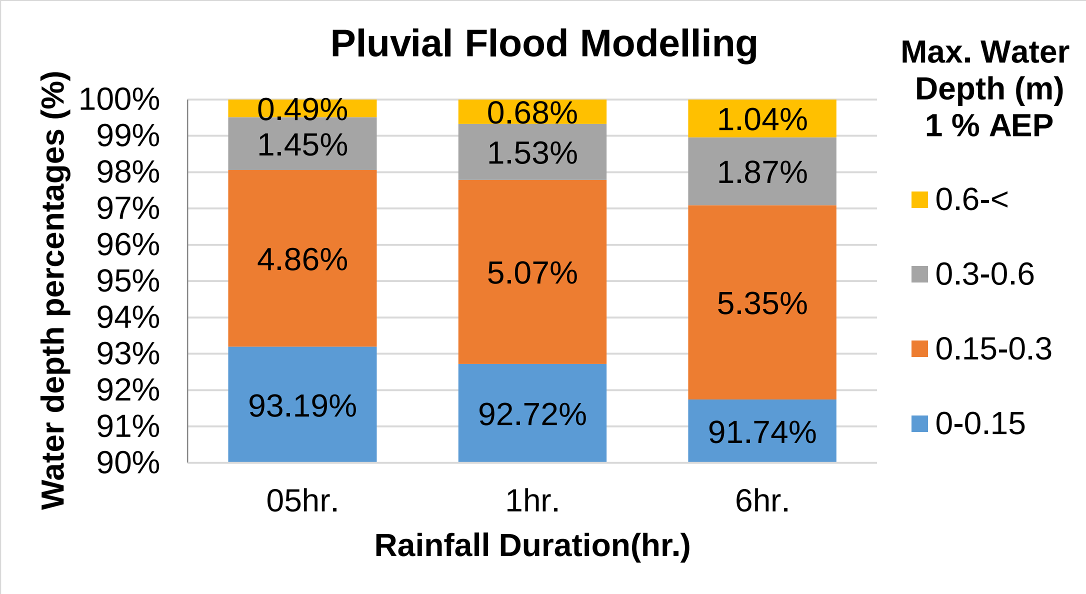

Figure 5.30 The percentages of the water depths (m) for rainfall durations

Figure 5.30 displays the percentages of the water depths (m) for various rainfall durations (0.5 hr., 1 hr., and 6 hr.).

It is apparent in Figure 5.29 that water depths become deeper when design rainfall events from for the 1 in 5-year to for the 1 in 100-year event. The locations of vulnerable places can be identified on the maps. In addition, when the rainfall duration becomes longer water depth can become higher for the same return period events (Figure 5.30).

5.3.4 Flood frequency analysis of the Farnley Beck (FB) catchment

This section aimed to determine the return period of the maximum discharge of the Farnley Beck (FB) sub-catchment. Initially, the rainfall events were designed for the 1 in 5 year, 1 in 10-year, 1 in 15-year, 1 in 25-year, 1 in 50-year and 1 in 100-year event and rainfall durations (D) were applied 0.5/1/6 hour for the 1 in 100-year event. Then, peak flow values were computed from these rainfall events. Meanwhile, return periods of the peak flow were determined by using the pooled method of statistical flood estimation procedure for the Farnley Beck (FB) sub-catchment. Next, the return periods of the statistical approach were used to determine the return periods of the computed peak flows from TUFLOW 2D direct rainfall model. Lastly, the return periods of the computed peak flow were compared to the return periods of the rainfall event. Table 5.4 indicates the relationship of the return periods between rainfall event and flood frequency for Farnley Beck (FB) sub-catchment.

Table 5.4 The relationship between the return periods

Rainfall Event T(year) D (h)	FB Computed Peak flow (m^3/s)	Return period of the Peak Flow (year) (Pooled method)	Peak flow value (Pooled method)
5 yr (4h)	3.97	2	10.18
15 yr (4h)	9.38	5	13.4
30 yr (4h)	12.84	10	15.65
50 yr (4h)	16.69	15	16.99
100 yr (4h)	23.99	25	18.76
100 yr 0.5h	3.117	30	19.42
100 yr 1 h	8.918	50	21.35

100 yr 6 h	24.77	75	22.985
		100	24.20
		200	27.36

Table 5.4 displays the flood frequency and the relationship of return period between the rainfall and peak flow.

The first column shows the rainfall return period and duration of the design rainfall events. The second column displays the peak flow values of the discharge at the outfall point Farnley Beck basin from each design rainfall events. The return period of the peak flow from the pooled method of the statistical flood frequency approach is shown in the third column. The fourth column displays the peak flow values from the pooled method of the statistical flood frequency approach.

This could be said that from Table 5.4

The 1in 5-year rainfall event cannot create a flood event.

The 1in 15-year rainfall event can create the 1 in 2-year flood even,

The 1 in 30-year rainfall event can create the 1 in 5-year flood event,

The 1 in 50-year rainfall event can create the 1 in 15-year flood event,

The 1 in 100-year rainfall event can create the 1 in 100-year flood event.

When the impact of rainfall duration is assessed for the 1 in 100-year rainfall event, it is observed that short rainfall durations could not cause flood event such as 0.5-hr. 1-hour rainfall duration of the 1 in 100-year event could cause nearly for the 1 in 2-year flood event. The 6-hour rainfall duration of the 1 in 100-year rainfall event could nearly cause the 1 in 100-year flood event.

However, the FEH recommends using observed annual maximum flood data where are available (Kjeldsen and Jones, 2007). The FEH noted that the uncertainty of QMED estimation is generally larger than the uncertainty of QMED estimation from directly flood data (Kjeldsen et al., 2008).

To assess the relationship of return period between the rainfall and flood events, catchment soil characteristics can need to be investigated in detail. The season can influence the runoff as well. Usually, flow return period can be smaller than the return period of the rainfall event (Viglione and Blöschl, 2009). In addition, rainfall duration can influence flood magnitudes as well. If catchment size is small, short rainfall durations can create strong flood events (Viglione and Blöschl, 2009). Consequently, rainfall return period is not always the same as return period of the flood.

5.4 Conclusion

Pluvial flooding in Wortley Beck catchment was assessed by using a direct rainfall approach in this research. It can be used as an alternative to traditional rainfall-runoff models. The approach of the direct rainfall model consisted of two main sections. These were net rainfall estimation by using ReFH loss model and flood inundation simulation by using the 2D TUFLOW hydrodynamic model. The advantage of the TUFLOW 2D hydrodynamic model for this research was that peak flow values could be computed anywhere inside the research area. Hence, flow values can be computed for different rainfall events and flood frequency analysis can be applied in an ungauged catchment by using this method.

The model was used to analyse the effects of various rainfall events on the Wortley Beck catchment. The results display that

1. When the rainfall return period is changed from 1 in 50-year to 1 in 100-year, the rainfall depth of the rainfall event becomes higher.

2. Long duration rainfall events have lower peak rainfall depth (mm) in comparison to short duration rainfall events (0.5/1hr.) for the same return period, but the total rainfall depth value become larger for longer rainfall durations.

3. The probabilistic flood inundation maps display the drain area of the Wortley Beck River. When return period changed from the 1 in 5-year to a 1 in 100-year event in this research, the water becomes higher both on the surface and inside river channel. In addition, similar behaviour was observed when the rainfall duration became longer (from 0.5 hour to 6 hours for the 1 in 100-year rainfall event). However, the ratios of the water depth values display that majority of the water depth is lower than 0.6 m.

4. The peak flow of the Farnley Beck sub-catchment was also computed. The results shows that rainfall return period can be different from return period of the flood event.

In conclusion, it can be said that if the return period of a rainfall event is longer than the 1 in 30-year event, the surface flood event can become serious, but if the rainfall duration becomes longer, any event can have serious consequences.

Some limitations points of the research methodology to reach the aims were that there was not sufficient measured rainfall data. Therefore, design rainfall events were created as input for the direct rainfall model. Furthermore, drainage system data could not be provided for this research so that the loss for the drainage system could not be added to the model. Moreover, improvements and updates necessary to verify the methodology because the direct rainfall model is a new approach. Lastly, to capture the peak flow anywhere in the catchment requires the model running with a cell size smaller than 5 m. However, computation can take weeks or longer.

In summary, the outcomes of this chapter can be used to improve the flood resilience approaches, as well as assist to understand the relationship between rainfall and flow in ungauged catchments. In addition, the results can be used to better identify Wortley Beck catchment vulnerability to the pluvial flood risk.

Chapter 6 Combined fluvial and pluvial flooding

6.1 Introduction

The main motivation of this research is that the risk of combined flood events should be estimated by simulating the combined sources and pathways of the flood events in models. Floodwater depth and flood extent are estimated by simulating the combined fluvial and pluvial flood models in this research.

In this section of Chapter 6, firstly, the differences between pluvial and fluvial flood events in a catchment are explained. Secondly, the relationship between pluvial and fluvial flood events in an urbanised catchment is determined. Thirdly, the importance of the investigation of the combined fluvial and pluvial flooding is discussed.

Pluvial and fluvial flood events can have different flood pathways, and different event durations so that pluvial and fluvial flood events have been mostly seen as independent. The fluvial flood event can affect the floodplains by streams while a pluvial flood event can affect the lower local locations in urbanised basins (Chen et al., 2010; Bhattarai et al., 2015). Pluvial flooding can be on smaller spatial and temporal scales than fluvial flooding can (Rözer et al., 2016). Pluvial flood events can be seen sooner than fluvial flood event. Fluvial flood event can take time, and the consequences of the fluvial flooding can be observed after days or weeks because the river water level rises slowly (Chen et al., 2010).

Intense rainfall event and land use change might affect the fluvial and pluvial flood process in an urbanised catchment. Firstly, heavy precipitation can be a source of an intense surface runoff. The overflow on saturated soil or impermeable surfaces can result in a pluvial flooding. In addition, the surface runoff in the upstream location can be the source of discharge into the river channel and this could result in a fluvial flooding. Secondly, the land use change in a catchment can increase the ratio of the impermeable surfaces.

Urbanisation can cause fast runoff, overwhelmed drainage systems, and the settlements on the floodplains so that pluvial flooding can be seen on the floodplains. In addition, the settlements on the floodplains by urban streams can face to the fluvial flooding (Evans, 2004; Pitt, 2008; Chen et al., 2010; Apel, et al., 2015).

In summary, this could be said that the consequences of the rainfall events and impermeable surfaces on the floodplains by urban streams could create combined fluvial and pluvial flood events. Therefore, pluvial and fluvial flood events could be considered consecutively and dependently in these locations.

Fluvial flooding and local heavy rainfall events can be observed during the annual monsoon therefore both fluvial and pluvial flooding can occur at the same time in the tropical environments (Apel et al., 2015). Historically, there are some samples of combined fluvial and pluvial flood events in England. Surface water and Local River flooding were observed between 23 and 27 December 2013 from Dorset through Hampshire also Surrey to Kent (Thorne, 2014). In addition, pluvial flooding occurred in conjunction with the fluvial flood event in January 2005 at Carlisle (Falconer et al., 2009). A pluvial flood event was observed due to the limited capacity of the drainage system in the River Eden catchment, after a while a fluvial flood event was observed due to the limited capacity of the banks of the River Eden and its tributaries in the Carlisle in January 2005 (Shaw et al., 2011).

Naturally, the combined fluvial and pluvial flood events can occur. If flood events are considered separately, the hazard can be underestimated (Ashley et al., 2005; Burton et al., 2010; Chen et al., 2010). This can result that the flood defence systems cannot be used efficiently and to manage the flooding can be very difficult. Consequently, the approaches of simulation of the combined events should be generated. The outcomes of the simulations can be used to improve and update the flood risk management approaches and flood resilience tools (Houston et al., 2011).

6.2 Methodology of the combined fluvial and pluvial flooding

The most of the research in the literature has assessed fluvial and pluvial flood events independently and the flood extents maps have been overlapped to observe the combined floods. However, this method can have some limitations. For instance, firstly, if pluvial and fluvial flood events are simulated separately, the interactions of the sources and the interactions along on the pathway cannot be obtained and observed. Secondly, if the flood inundation maps of the pluvial and fluvial flood events are only overlapped, the water depth in the inundation area of the combined events could not be computed and the flood extents from combined events cannot be observed.

Alternatively, a method to assess the combined fluvial and pluvial flooding should be generated. Horritt et al. (2010) recommended two approaches; these were to compare independent flood inundation maps of the different flood events and to assess the dependency of the flood events at the sources. Lian et al. (2013) recommended researching the combination of the effect of flood probability and consequences as a single risk function. Breinl et al. (2015) recommended adding a hydrodynamic model to simulate the flood inundation maps to improve the combined flood risk assessment.

The aim of this methodology is to assess the interactions between the fluvial pluvial flood events on the floodplains in urban stream basins. Thus, flood risk from the combined fluvial and pluvial flooding on the urbanised floodplains by urban streams can be observed. This methodology was applied to the Lower Wortley Beck area. The Lower Wortley Beck area is suitable for this research because there is a fluvial flood risk by the Lower Wortley Beck, and urbanised areas are located by the stream. Pluvial flood risk can also be observed on the impermeable and lower locations by the stream.

6.2.1 Modelling approach of the combined fluvial and pluvial flooding on the floodplain

The methodology of the combined fluvial and pluvial flood simulations is explained in this section. The modelling approach is to produce and examine the combined fluvial flooding and pluvial flooding on the floodplain in urban stream basins. In order to simulate the combined fluvial and pluvial flood events, both inflow hydrograph and net rainfall hyetograph were included in the same model.

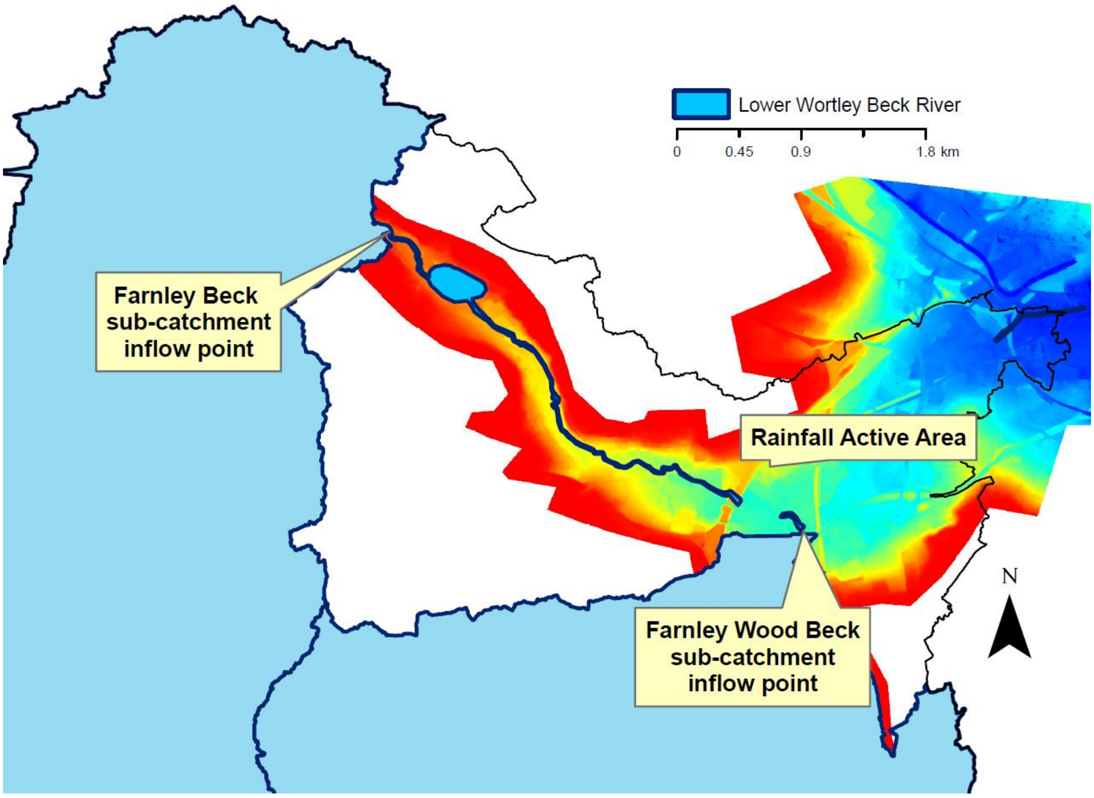

Figure 6.1 The combined fluvial and pluvial flood modelling at the Lower Wortley Beck area

The 2D domain of the Lower Wortley was activated for both fluvial and pluvial flooding (Figure 6.1). Inflows from the Farnley Beck and Farnley Wood Beck basins entered into the Lower Wortley Beck, and net rainfall hyetograph of the Lower Wortley Beck area were applied on the 2D domain of the Lower Wortley area. Inflows enter the river channel at the same time with the rainfall event starts. Inflow points of the sub-catchments, active area of the rainfall event, and 1D river channel can be seen in Figure 6.1 for this modelling approach.

The Flood Modeller Suite 1D River model was set up with initial conditions and inflow events. River nodes of the Lower Wortley Beck channel were used. The model was run with the hydrograph time that was 20 hours. The 1D model time step was 1 second. Roughness values of the 1D river channel were selected between 0.030 and 0.045 (Atkins, 2004). The Flood modeller Suite 1D Model was linked with the 2D scheme of the TUFLOW software. 2D model time step was 2 second. 2D control file was used to manage the 2D domain geometry for the active area, to manage the boundary condition commands of 2D net rainfall events, and to manage the 2D domain topography from the material file of roughness values. Roughness values of the 2D surface can be found at Table 5.3 Master Map land use assessment. Elevation data was used for both river channel and Lower Wortley surface area. Model topographical area (DEM) can be found in Figure 6.1.

Net rainfall hyetograph was applied on the impermeable and permeable surfaces of Lower Wortley Beck area (Figure 6.2). The net rainfall profiles were designed for the 1 in 100-year event and for 4-hour rainfall duration. Net rainfall event was added into the 2D domain boundary condition database in the model.

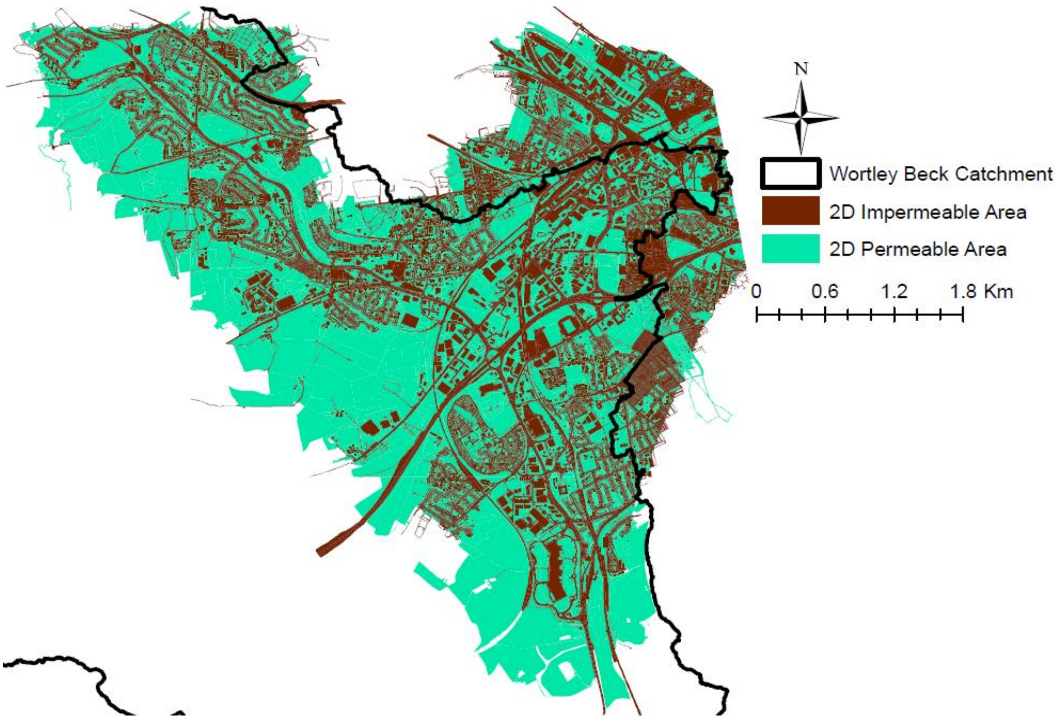

Figure 6.2 2D Rainfall boundary condition control area

This modelling approach was applied by using tools are 1D Flood Modeller Suite version 3.7 linked to TUFLOW 2D software (version 2013-12-AD-IDP-w64). The model was run for 1D unsteady flow and 2D double precision. Model Grid cell size was 8 metre.

The results display the combination of river overflow and surface runoff on the floodplain, along with the Lower Wortley Beck.

6.3 Results of the combined fluvial and pluvial flooding

In this section, fluvial and pluvial flooding and their interaction on the floodplain by the Lower Wortley Beck are assessed.

The assessment considers three comparison steps:

1. Fluvial flooding and single event simulation,
2. Independent fluvial and pluvial flood events,
3. Combined pluvial and fluvial flood events,

The assessment parameters were taken to be water level data and flood inundation extents (as assessed via comparison of inundation maps that also serve to indicate flood risk at the Lower Wortley Beck catchment) from the simulation results. The models of fluvial flooding, single event simulation, pluvial flooding, and combined fluvial and pluvial flooding were set-up for the 1 in 100-year event, with the ratio of impermeable surface was for the year of 2016 being consistently used. Arc MAP 10.2.2 tool was used to produce the maps.

Water level graphs were produced for specific observation points for all simulation for comparison, these locations points are shown in Figure 6.3. Flood inundation maps were produced to assess the flood risk at the Lower Wortley Beck area.

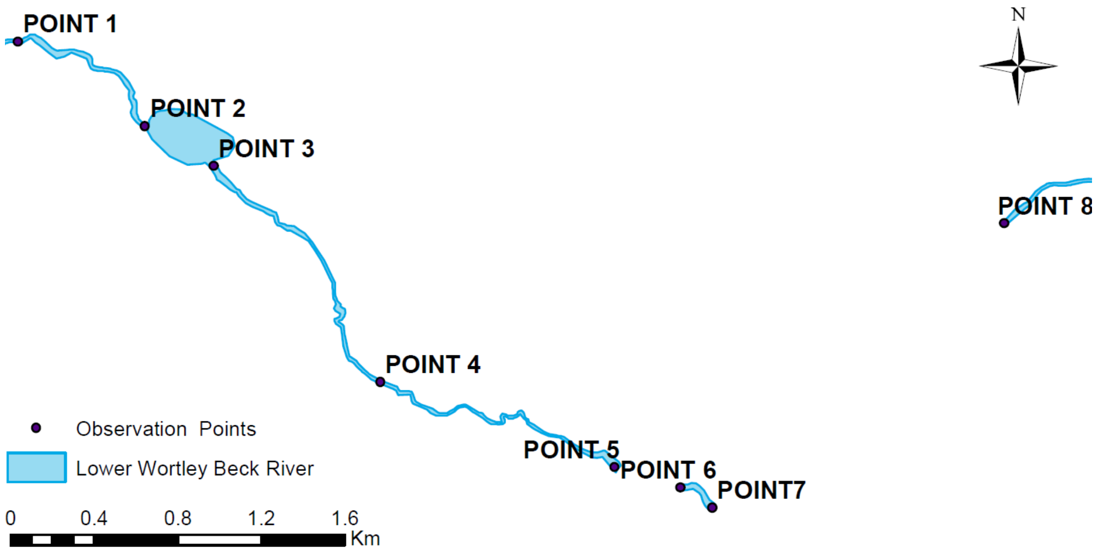

Figure 6.3 Observation points on the Lower Wortley Beck

Figure 6.3 displays the observation points used to compare the water levels of different flood events. They are at specific locations that are each useful points to indicate flood behaviours in the sub-regions of the catchment.

Point 1 located downstream of the Farnley Beck basin thus the impact of the inflow from the Farnley sub-catchment can be observed.

Point 2 lies just before the river enters into the reservoir. Data from this point allows flood events to be identified between point 1 and point 2.

Point 3 is located just below the reservoir so the impact of the reservoir can be determined.

Point 4 is the upstream extent of where fluvial flooding occurs.

Point 5, 6, and 7 are within the flood inundation area. This area is between Gelderd Road and A6110 transportation link M621 highway. The points of these locations are important because these areas have settlements and transportation links. The inflow from Farnley Wood Beck enters in this location. The backwater effect observed here might be the reason for the flood event due to overcapacity of the culvert at this location. Both pluvial and fluvial flooding can be seen in these locations while a combination of events can increase the risk here as well**.** Point 8 is toward the end of the catchment after longer culvert and gives as an indication of the water that is able to flow through the catchment.

6.3.1 Assessment of the fluvial flood model and single event flood models

Fluvial and single event model simulations were set-up for the 1 in 100-year event, with the urbanisation scenario was for the 2016 year. The same 1D /2D linked fluvial flood model was used for each simulation.

Inflows were added from Farnley Beck and Farnley Wood Beck sub-catchments for the fluvial flood simulation. In addition, the lateral flow was included in the fluvial system for the single event simulation. The lateral flow was computed by using the rational method to estimate the peak discharge at the outlet of the New Farnley Beck basin. The peak flow was used to display the impact of the drainage system outfall on the downstream fluvial flood risk. The impact of the outfall indicates the resulting difference between the fluvial flooding and the single event simulation in the catchment.

A.) Comparison of the computed water levels between fluvial and single event simulations

The impact of the peak discharge at the outfall of New Farnley area on the water level can be observed from the examination of Figures 6.4, 6.5 and 6.6 for the Point 3, 4 and 5. The points can be seen in Figure 6.3. Point 3 is the location where the entrance of lateral flow. The impact of the outfall shows the difference between the fluvial flooding and the single event simulation in the catchment.

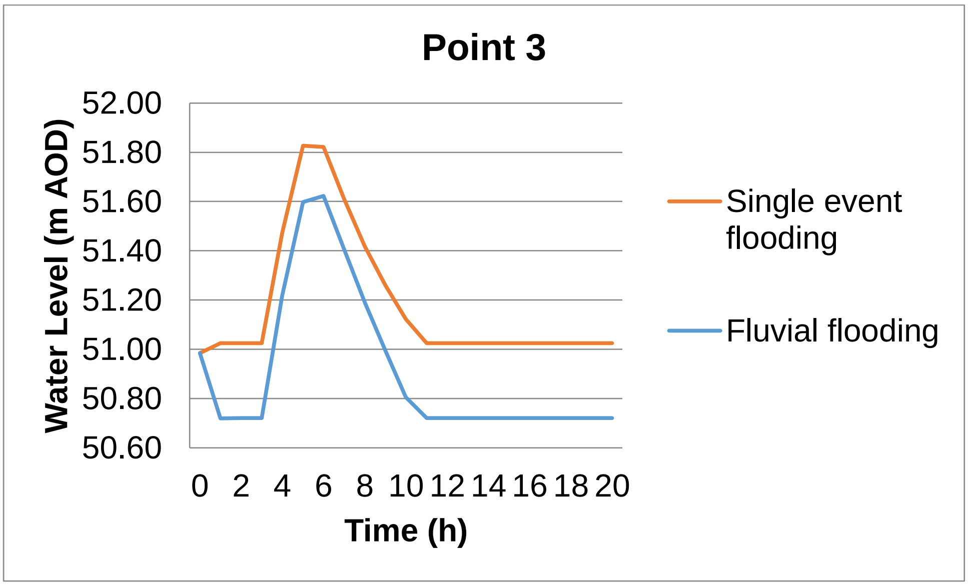

Figure 6.4 The water level at Point 3

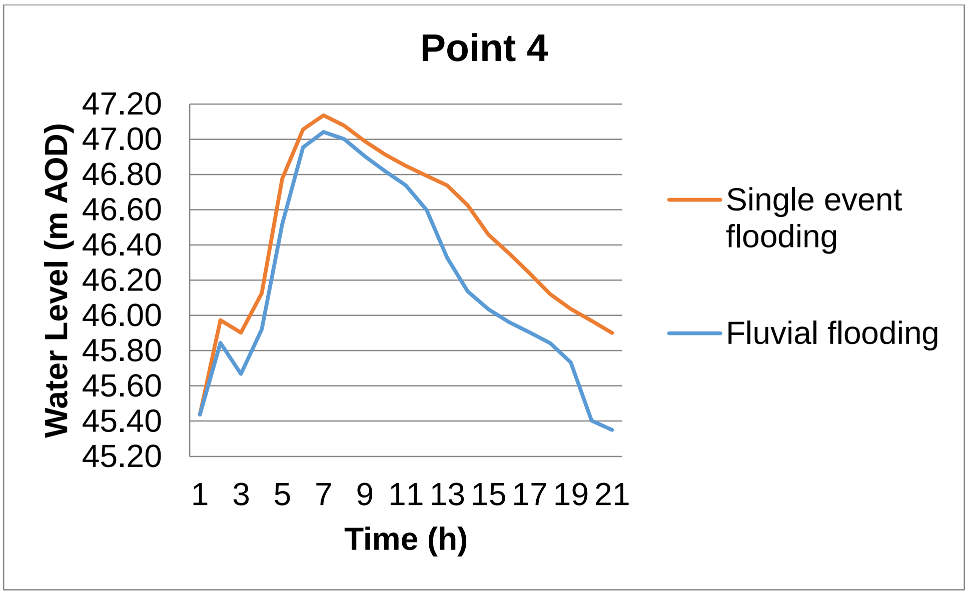

Figure 6.5 The water level at Point 4

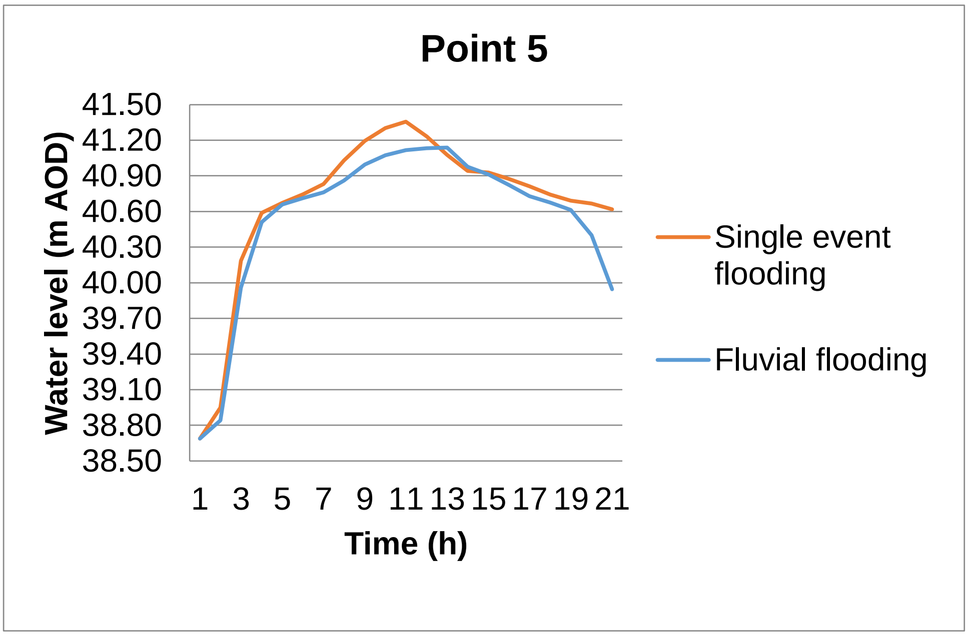

Figure 6.6 The water level at Point 5

Single event simulation displays higher water levels than fluvial flooding because of the impact of the peak discharge from the outlet of New Farnley Beck basin.

B.) Comparison of the flood inundation maps between fluvial and single event simulations

The impact of the lateral flow from the New Farnley on the Lower Wortley Beck area can be observed in Figure 6.8. OS 1:25 000 Scale Colour Raster was used for background map.

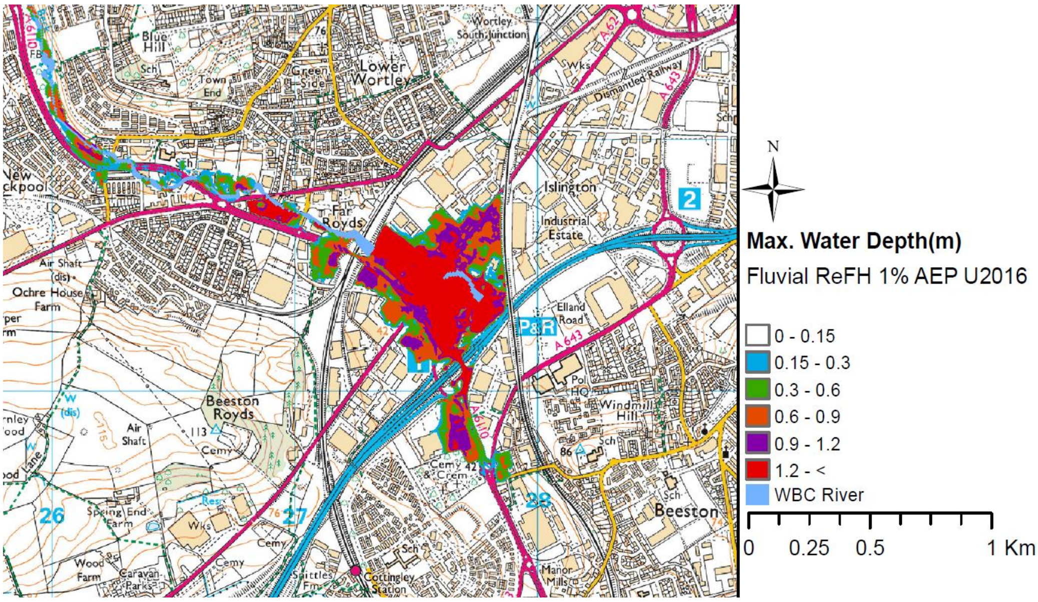

Figure 6.7 Fluvial flood inundation map

The fluvial flood inundation area can be seen in Figure 6.7 for the 1 in 100-year event.

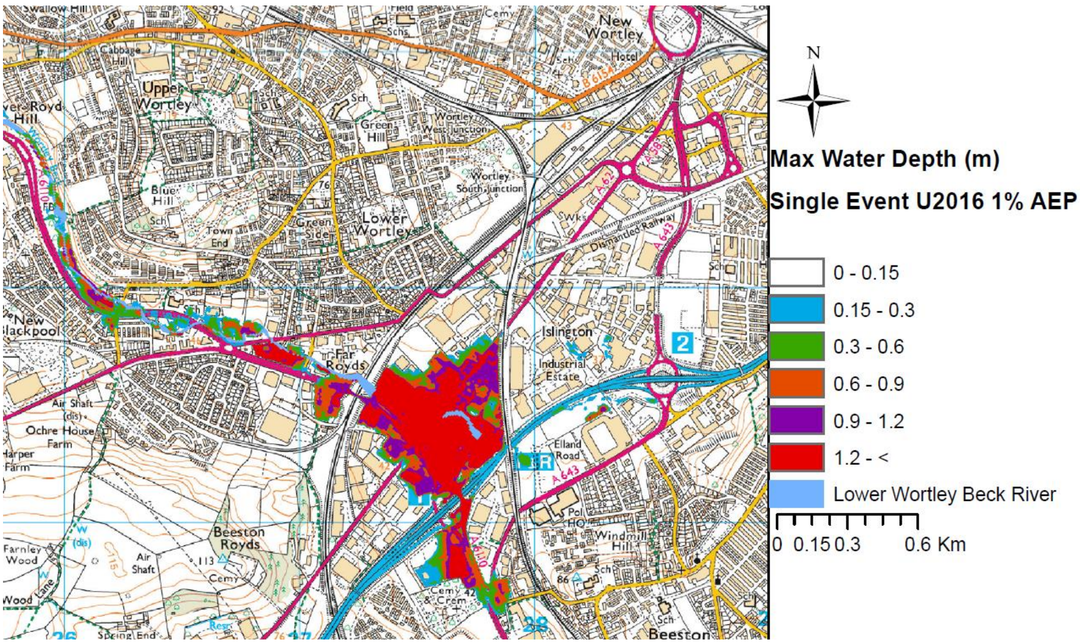

Figure 6.8 Single flood inundation map

The flood inundation area of the single event simulation can be seen in Figure 6.8 for the 1 in 100-year event.

In summary, the outfall from New Farnley caused higher water level, water depth, and larger flood extent area on the Lower Wortley Beck area.

6.3.2 Assessment of discrete pluvial and fluvial flooding

The discrete fluvial and pluvial flooding was designed for the 1 in 100-year event and for the impermeable surface of the 2016 year in the catchment. Inflows from the Farnley Beck and Farnley Wood Beck sub-catchments were estimated for the fluvial flooding. Hyetograph of the Wortley Beck catchment was estimated for the pluvial flooding. The 1D link 2D river model (Flood Modeller Suite/TUFLOW) was used for fluvial flooding and the rainfall-runoff model (2D TUFLOW) was used for the pluvial flooding.

The aim at using these arrangements was to observe the independent fluvial and pluvial flood processes in the catchment. Thus allowing flood risk from fluvial and pluvial to be identified in the catchment.

The fluvial flood event consists of both baseflow (initial conditions) in the river channel and inflow from the upstream sub-catchment. The pluvial flood event uses the rainfall-runoff process from the Wortley Beck catchment. In order to assess these events and detailed inspections, the focus of this research was on the Lower Wortley Beck area.

A.) Comparison of the computed water levels between fluvial and pluvial flood events

The results of this section display that the comparison of the computed water levels between fluvial and pluvial flooding. The water level data were computed from the river model for fluvial flooding, and from the rainfall-runoff model for pluvial flooding. The results are shown in Figure 6.9 to 6.13 for the observation points (described in Figure 6.3).

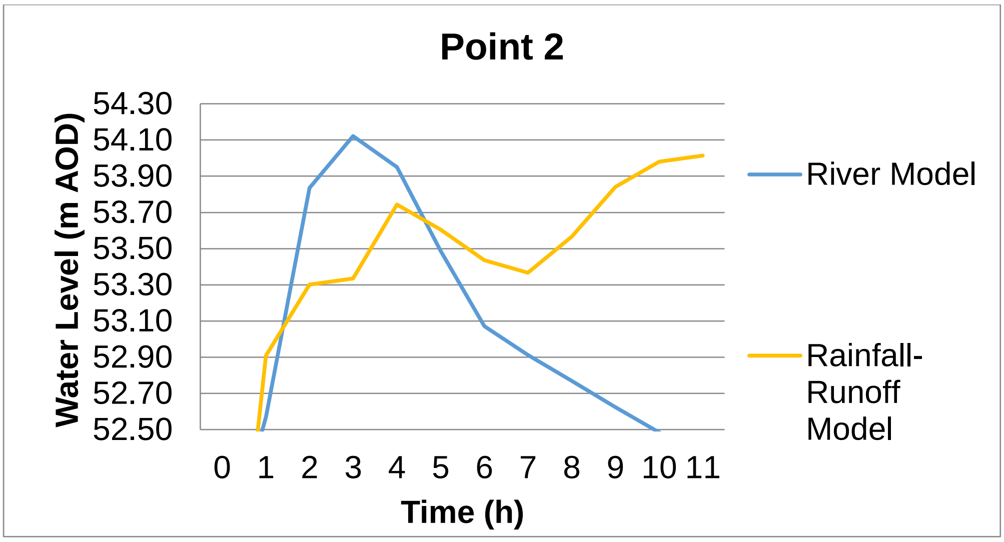

Figure 6.9 The water levels at Point 2

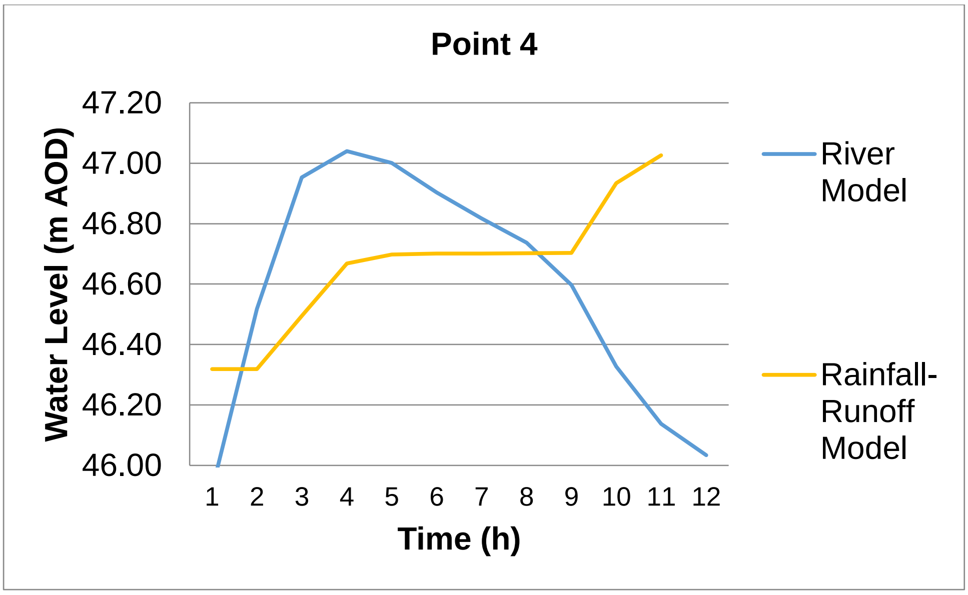

Figure 6.10 The water levels at Point 4

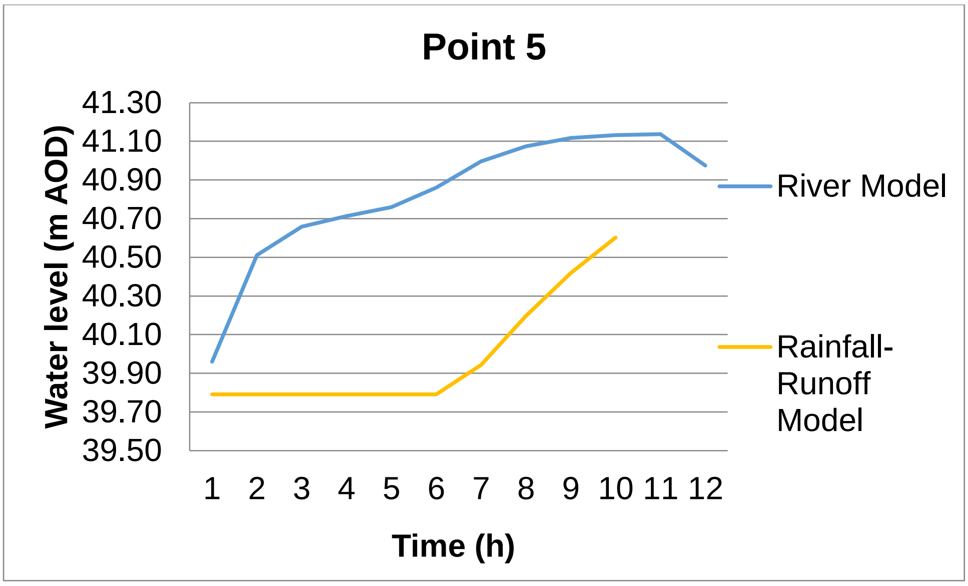

Figure 6.11 The water levels at Point 5

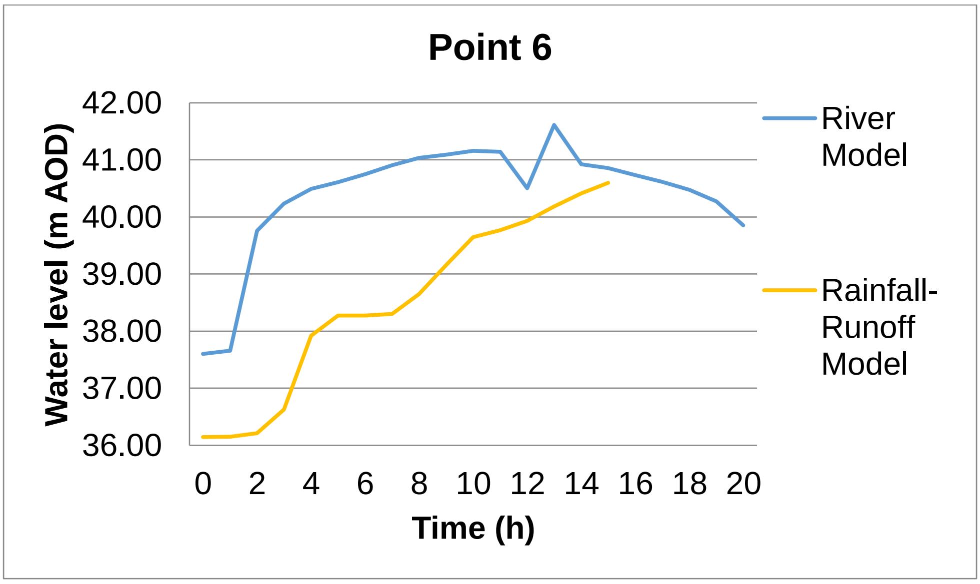

Figure 6.12 The water levels at Point 6

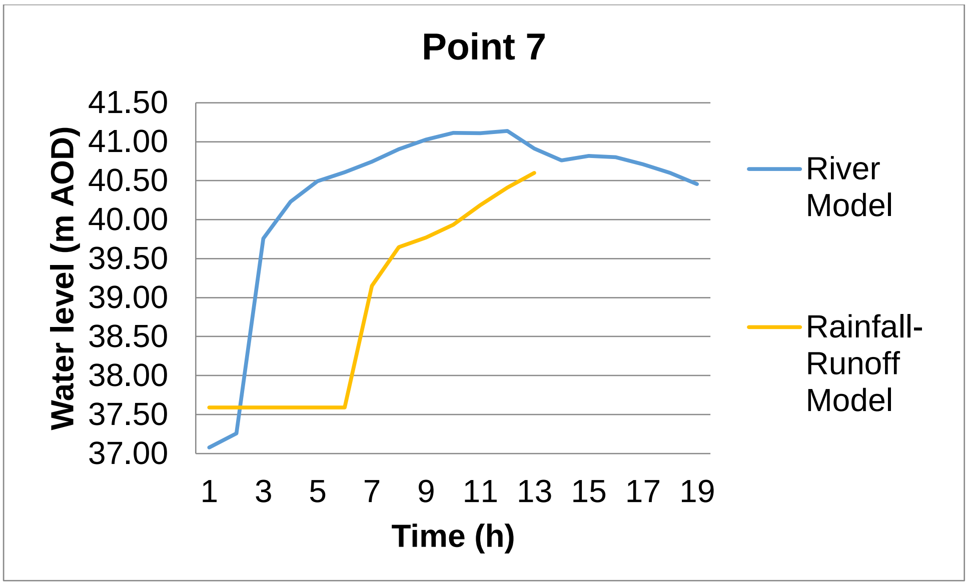

Figure 6.13 The water levels at Point 7

The water levels from the fluvial flooding are higher than from those for the pluvial flooding (see Figures 6.9 to 6.13). However, the values of the pluvial flooding virtually reach to the water levels of the fluvial flooding. This could mean that fluvial flooding is fast when inside the river channel while pluvial flooding takes more time due to the runoff being slower and longer.

B.) Comparison of the flood inundation maps between fluvial and pluvial event simulations

The probabilistic flood inundation maps with maximum depth (m) scales were created to assess of fluvial flood risk and pluvial flood risk at Lower Wortley Beck area.

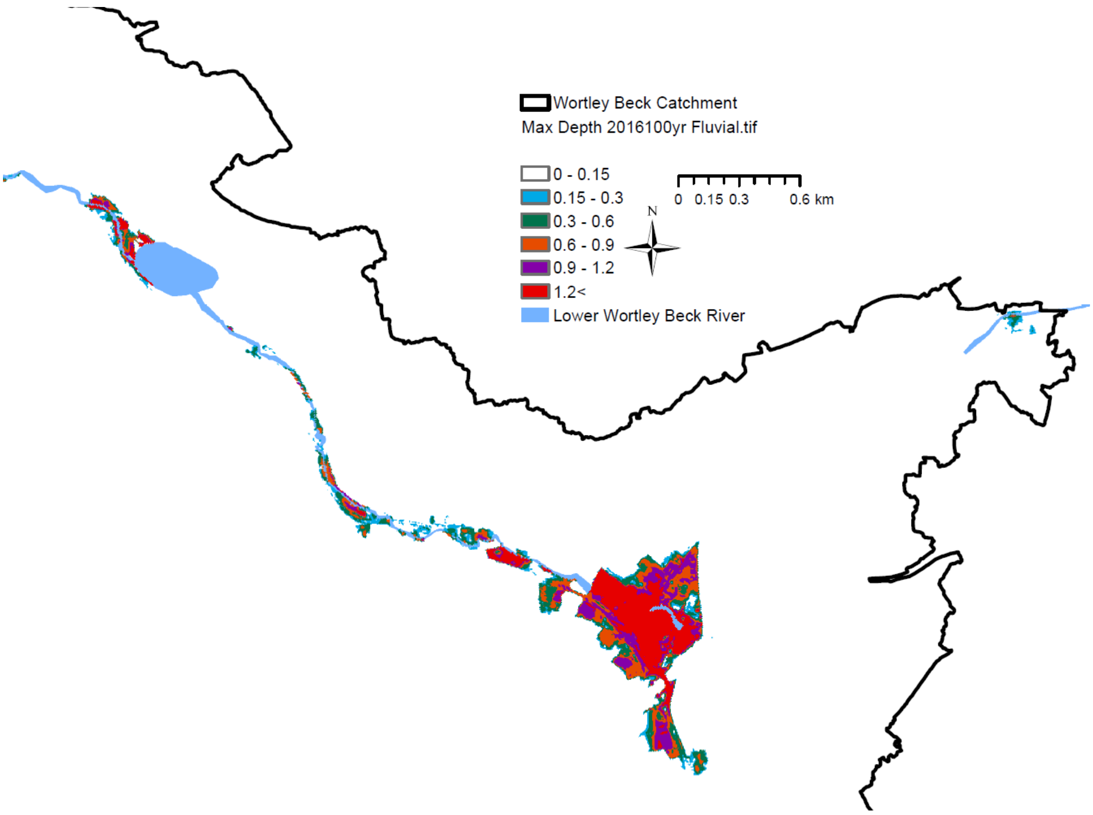

Figure 6.14 Fluvial flood inundation map

Fluvial flooding of the 1 in 100-year event on the Lower Wortley Beck area can be seen in Figure 6.14.

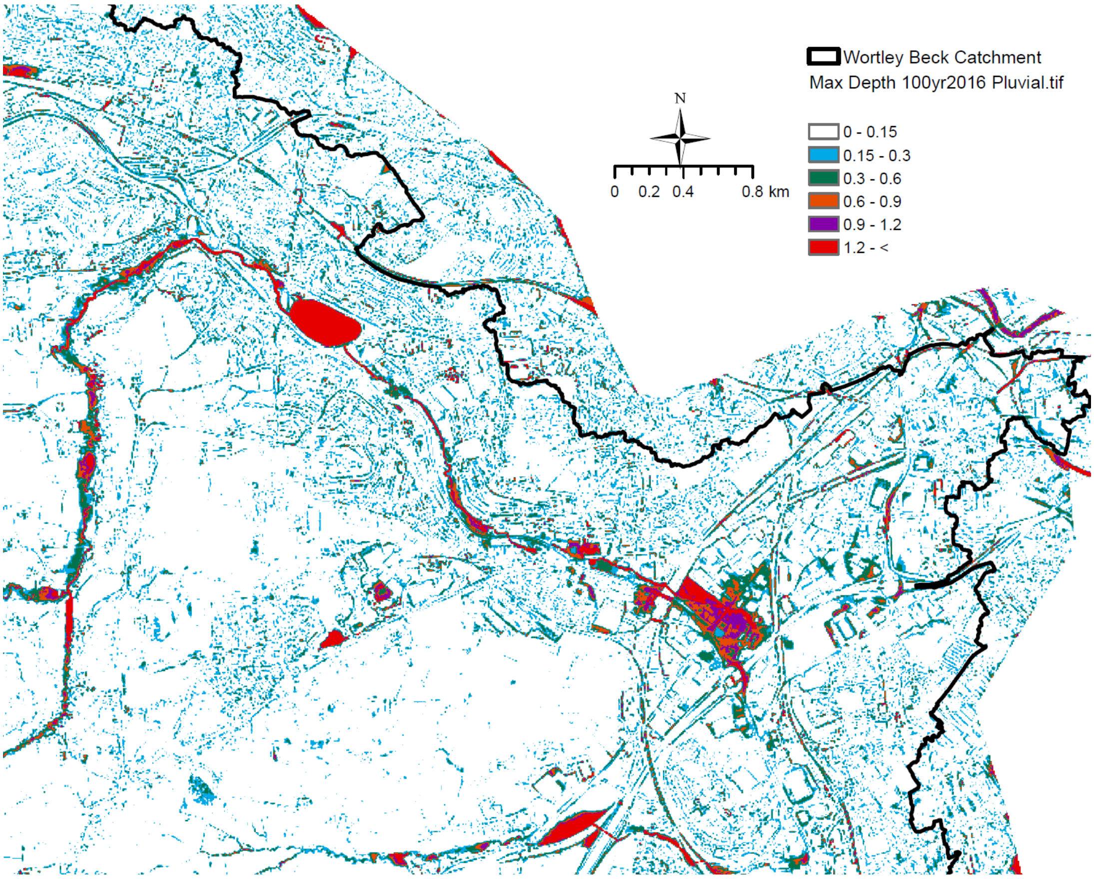

Figure 6.15 Pluvial flood inundation map

Pluvial flooding on the Lower Wortley Beck area is shown in Figure 6.15. This map displays the rainfall-runoff event from the rainfall event of the 1 in 100-year event on the Wortley Beck catchment. Pluvial flooding was simulated for the Wortley Beck catchment. This approach did not have river channel and urban drainage system within the 2D model.

Figure 6.14 and Figure 6.15 were produced to enable comparison of the independent fluvial and pluvial flooding.

Figure 6.14 and Figure 6.15 display similar locations by Lower Wortley Beck where there is a higher risk of flooding.

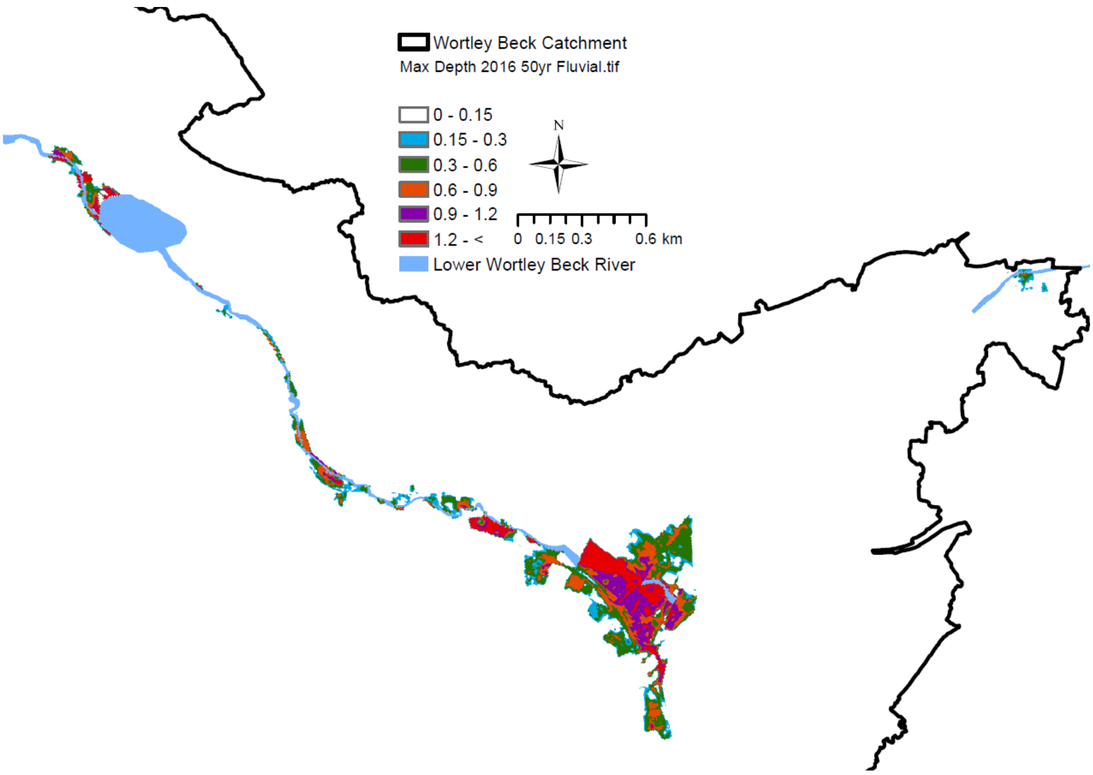

Figure 6.16 Fluvial flooding 2 % AEP on the Lower Wortley Beck area

Fluvial flooding of the 1 in 50-year event on the Lower Wortley Beck area is shown in Figure 6.16.

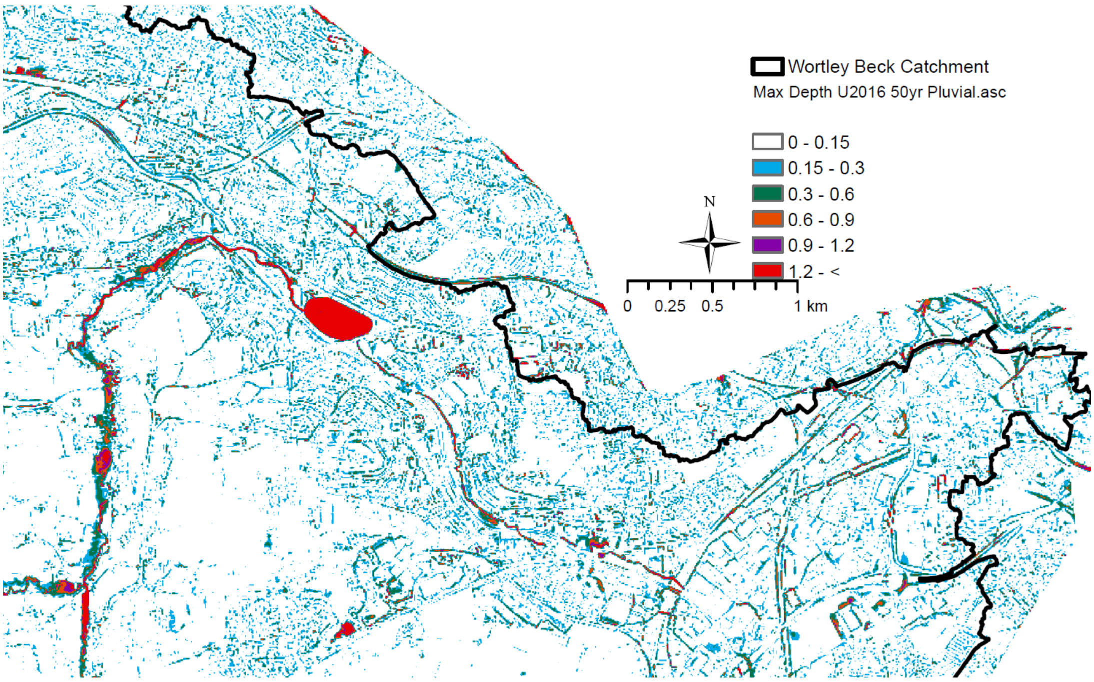

Figure 6.17 Pluvial flooding 2 % AEP on the Lower Wortley Beck area

Pluvial flooding on the Lower Wortley Beck area displayed in Figure 6.17. This shows the result of the rainfall-runoff event from rainfall event of 1 in 50-year event on the Wortley Beck catchment. Again, this approach did not have river channel embedded within the model.

The limitation of the analysis of the discrete fluvial and pluvial flooding maps is that water levels of the same points inside the flood inundation area of fluvial flooding and pluvial flooding cannot be merged so flood extent cannot be quantified directly from this figure.

6.3.3 Assessment of the combined pluvial and fluvial flood events

The effects of the combined fluvial and pluvial flooding on the flood risk are assessed in this section. The fluvial flood model was simulated by using the 1 in 100-year event of 20-hour inflow hydrograph, and pluvial flood event was simulated by using the 1 in 100-year event of 4-hour duration net rainfall hyetograph. The ratio of the impermeable surface was the year of 2016. This map was produced by combining inflow hydrographs and rainfall hyetographs and to observe flood risk on the floodplains at the Lower Wortley Beck area from combined flood events.

A.) Probabilistic flood inundation maps of the combined pluvial and fluvial flooding

Probabilistic flood inundation maps are used to display the combination between rainfall and river flow on the floodplain. From these, it is possible to observe the combined fluvial and pluvial flood events in the Lower Wortley Beck area.

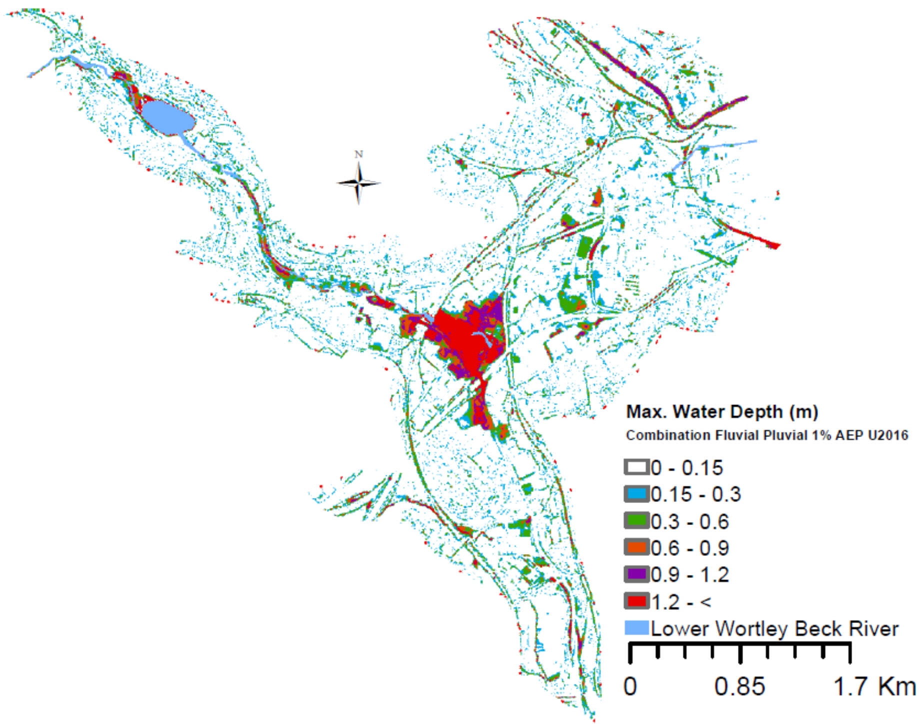

Figure 6.18 Combined fluvial and pluvial flooding

Combined fluvial and pluvial flooding of the 1 in 100-year event is displayed in Figure 6.18

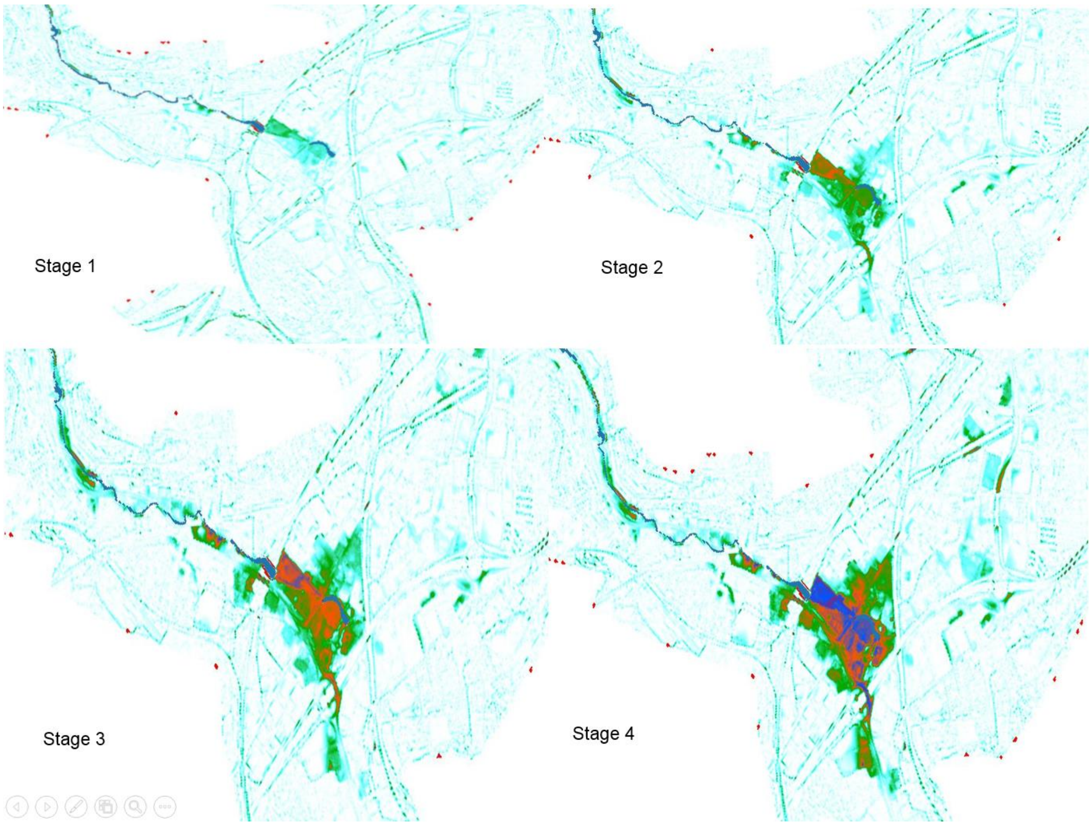

Figure 6.19 Combined fluvial and pluvial flooding water depth/ stages (1%AEP)

The processes of the combined fluvial and pluvial flooding can be seen in Figure 6.19. Stages display the flood inundation area at different times from the modelling at the Lower Wortley Beck area.

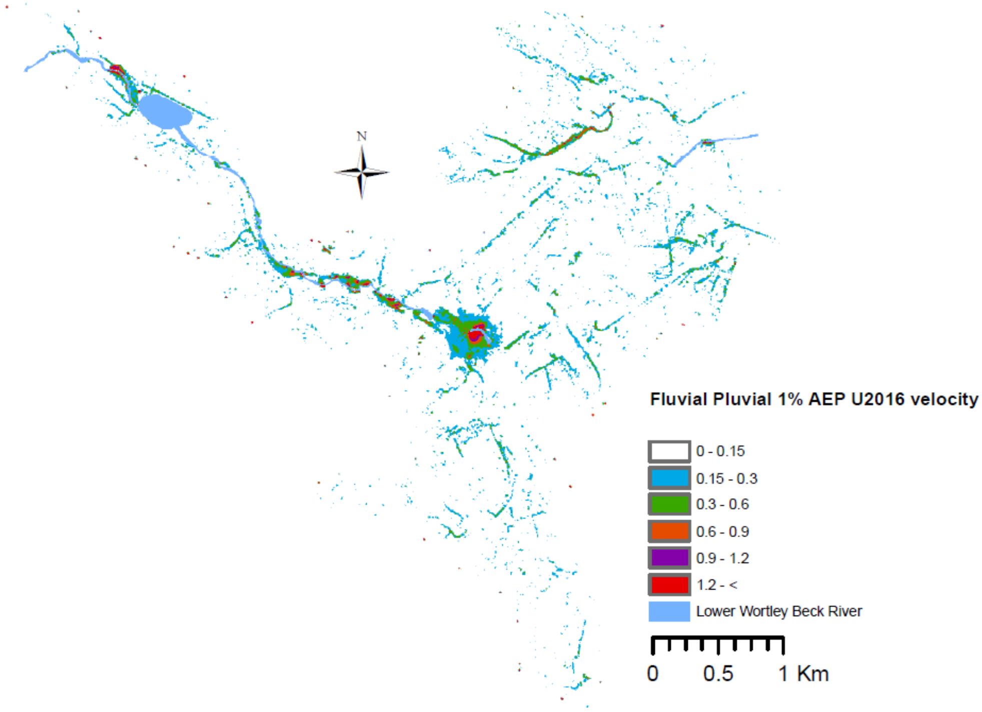

Figure 6.20 Combined fluvial and pluvial 1 %AEP flooding velocity map

The velocity (m/s) of the combined fluvial and pluvial flooding can be seen in Figure 6.20. The Gelderd Road location at the Lower Wortley Beck area is shown to be within the flood risk area.

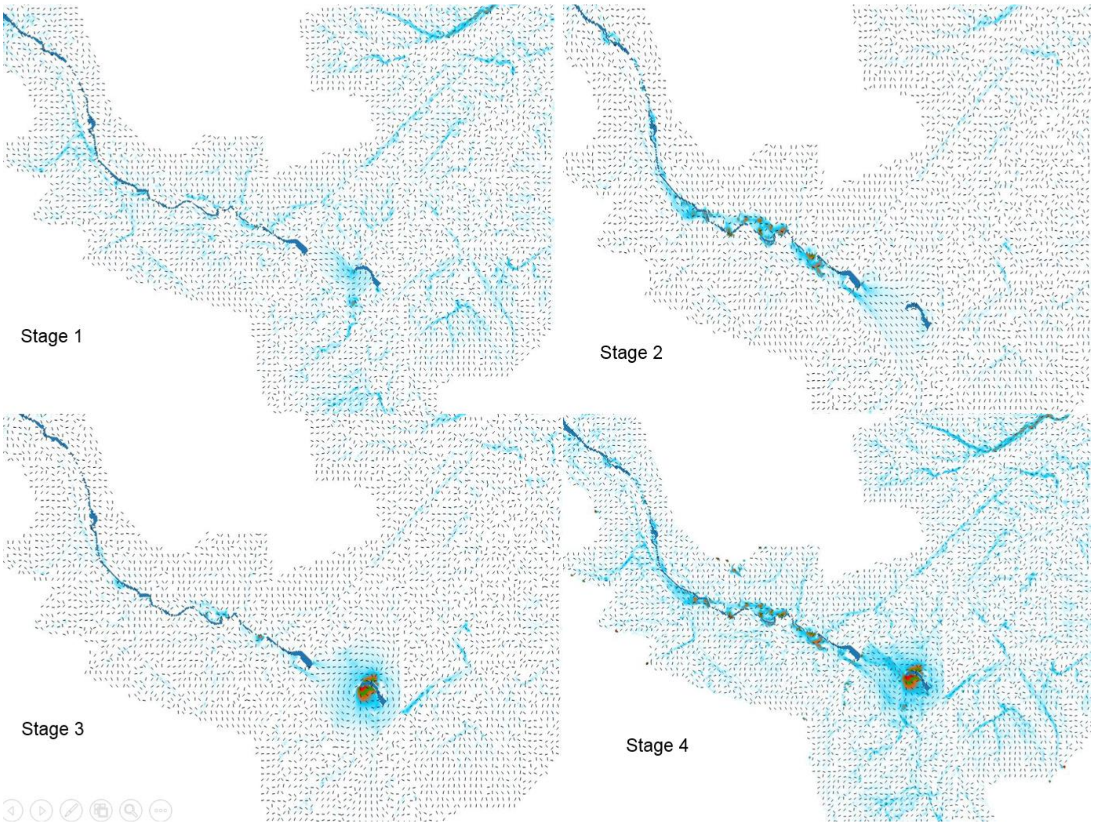

Figure 6.21 Combined fluvial and pluvial flooding 1% AEP (velocity /stages)

The velocity (m/s) of the combined fluvial and pluvial flooding can be seen in Figure 6.21. Stages display the velocity movement for different times of the modelling at the Lower Wortley Beck.

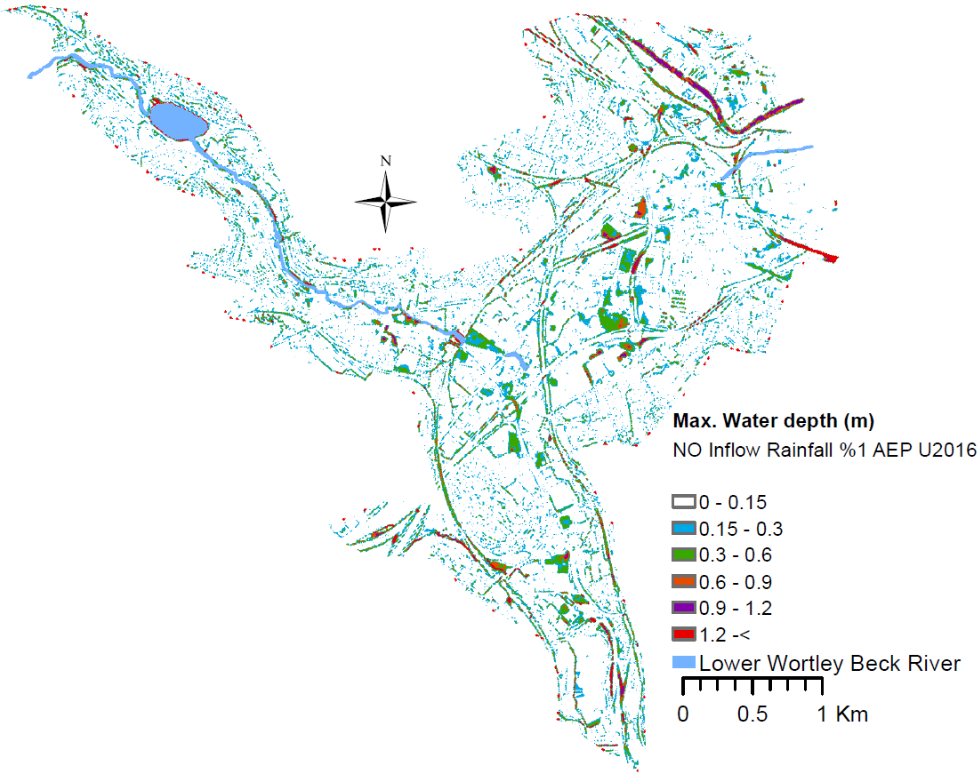

Figure 6.22 Pluvial flooding with the fluvial flood (no inflow from upstream)

The pluvial flooding simulation was designed for the 1 in 100-year rainfall event with the sole baseflow of the Lower Wortley Beck and no inflow from sub-catchments. The flood inundation area of this event can be seen in Figure 6.22. In addition, the effects of inflows on the fluvial flooding at the lower Wortley Beck area can be observed from the pluvial flooding map of the Lower Wortley Beck area (Figure 6.22) by comparing with Figure 6.18.

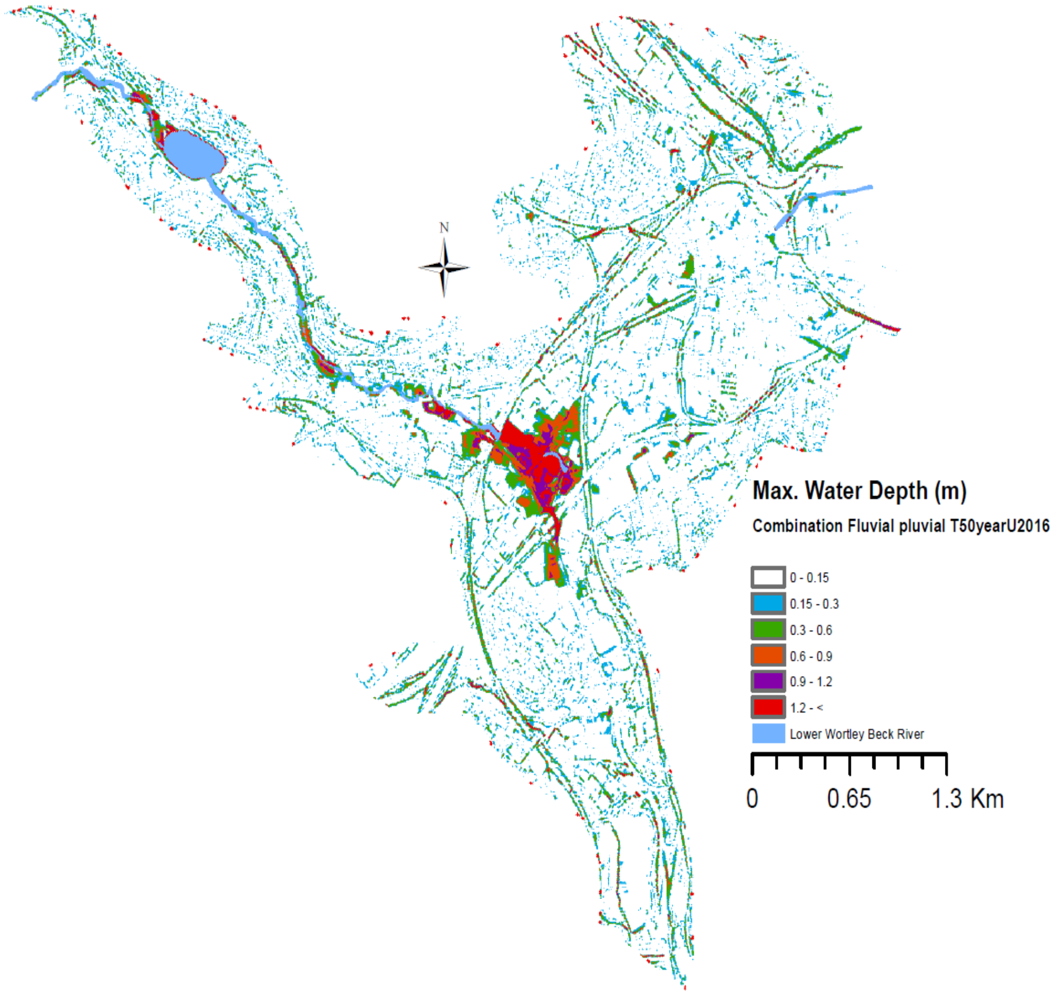

Figure 6.23 Combined fluvial and pluvial 2 %AEP flooding on the flood plain

The flood inundation area of the combined fluvial and pluvial flooding on the floodplain for the 1 in 50-year event can be seen in Figure 6.23.

In conclusion, the combined fluvial and pluvial flooding maps show the merged water depth and flood extent along the river channel from both river flow and rainfall.

6.3.4 Discussion of the combination fluvial and pluvial flooding at the Lower Wortley Beck area

This section presents the significance of the assessment of combined fluvial and pluvial flooding. The outcomes of combined fluvial and pluvial flooding were compared to the outcomes of only fluvial flooding, to the outcomes of the single event simulation, and to the outcomes of discrete fluvial and pluvial flood events for the assessment. To examine the outcomes, water level, water depth, and flood extent were used.

A.) Comparison of water levels between combined fluvial and pluvial flooding and only fluvial flooding

The impact of the pluvial flooding on the fluvial flooding was assessed by comparison of fluvial flooding to the combined fluvial and pluvial flooding for the 1 in 100-year event. This assessment was performed by comparing water level values of between fluvial flooding and combined fluvial and pluvial flooding. The graphs of water level values for each point can be seen between in Figures 6.24 to Figure 6. 28.

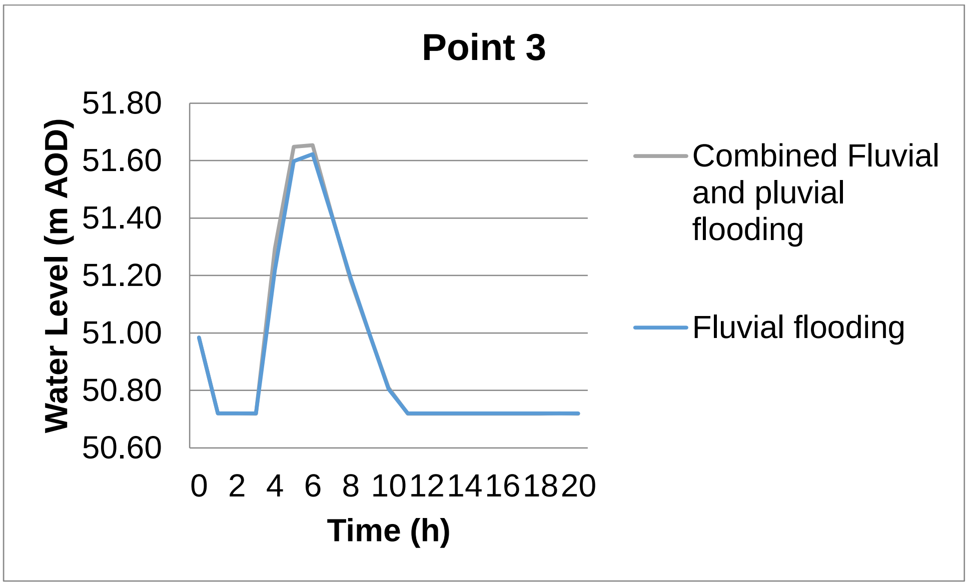

Figure 6.24 The water levels at Point 3

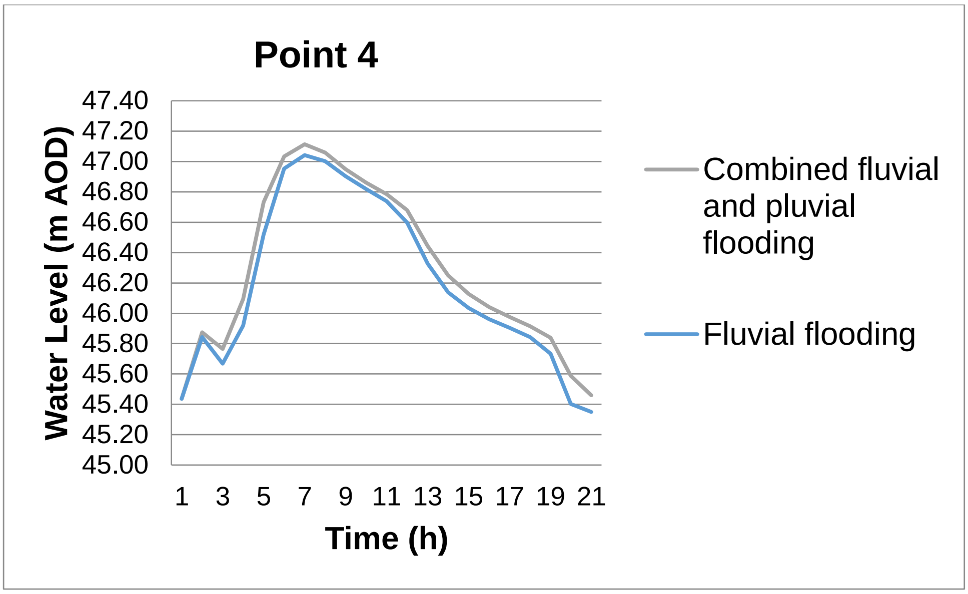

Figure 6.25 The water levels at Point 4

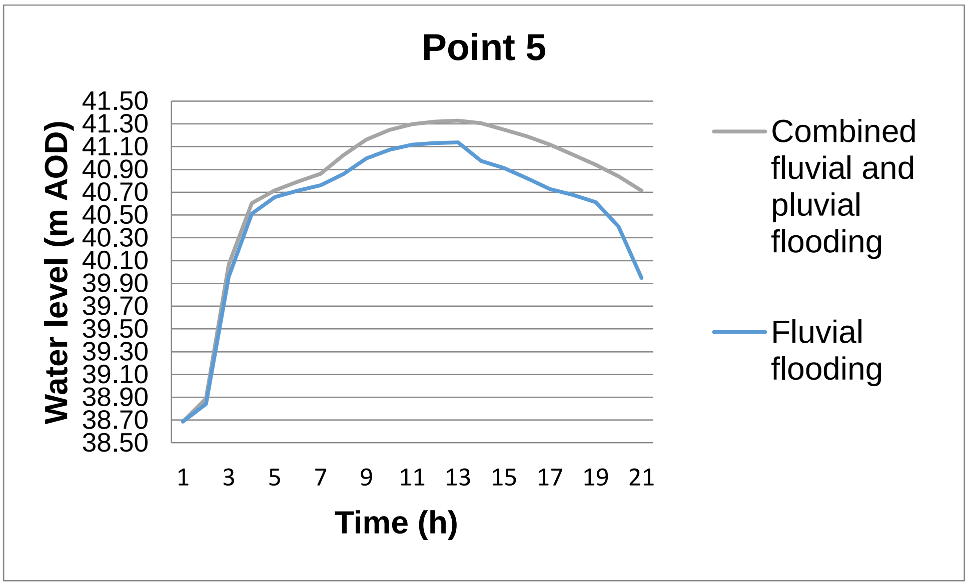

Figure 6.26 The water levels at Point 5

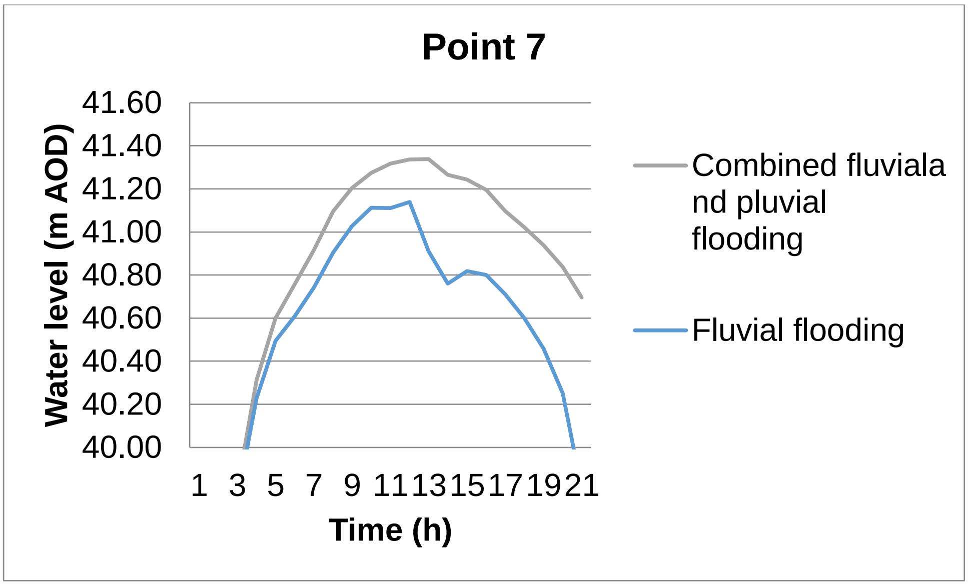

Figure 6.27 The water levels at Point 7

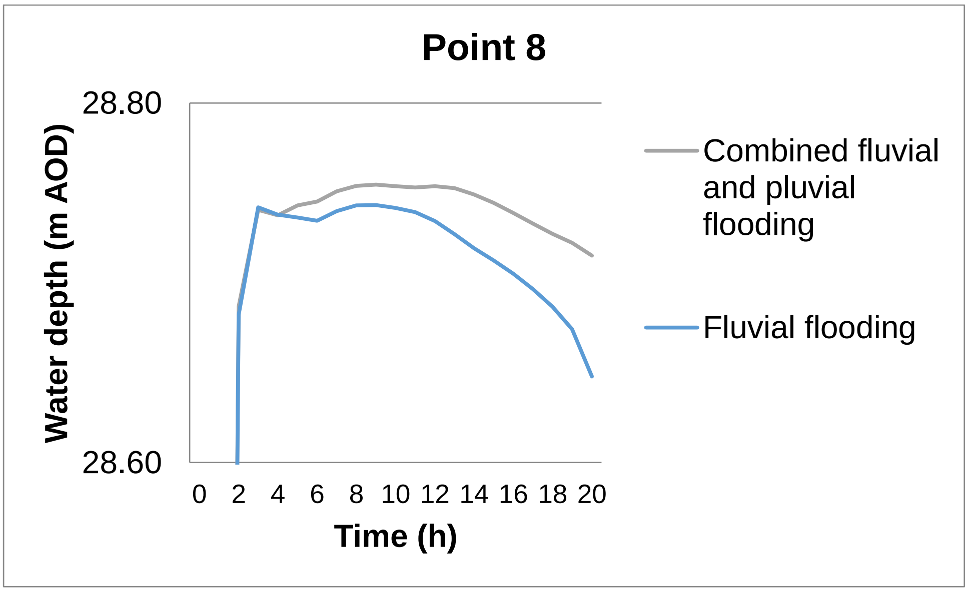

Figure 6.28 The water levels at Point 8

The figures (Figure 6.24 to Figure 6.28) show that the combined fluvial and pluvial flooding has higher water level value than only fluvial flooding. Results from Figure 6.24 and Figure 6.28 show that the combined fluvial and pluvial flooding can be dangerous than sole fluvial flood event.

B.) The impact of the combined fluvial and pluvial flooding on the water level in the flood extent

Fl1 and FI2 water level points were positioned inside the severe flood risk area (as shown in Figure 6.29). Both fluvial and pluvial flood events and backwater effects can be seen at the Fl1 and FI2 locations. Thus, the impact of the combined fluvial and pluvial flooding on the flood extent can be obtained for these points.

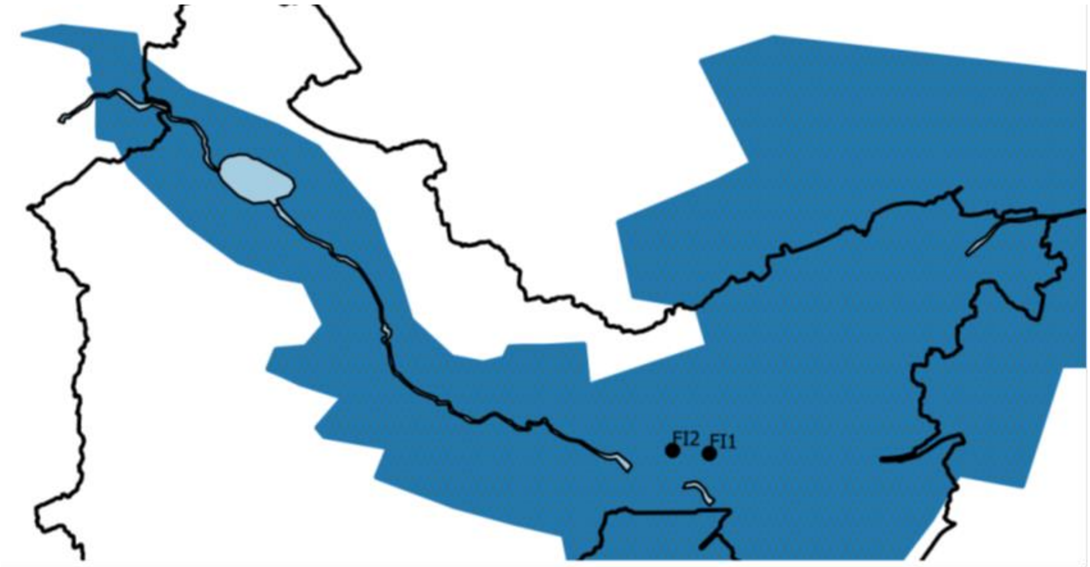

Figure 6.29 Fl1 and FI2 water level points

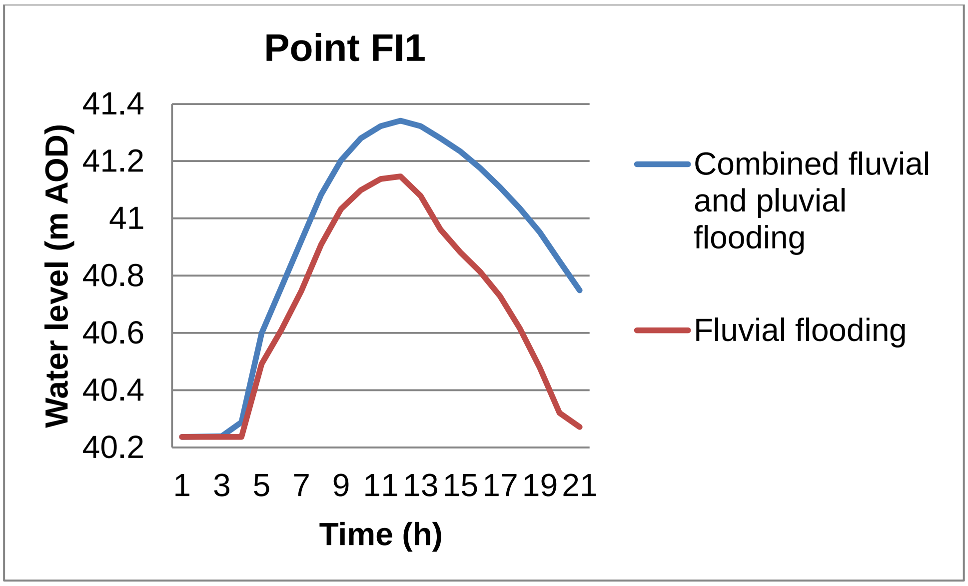

Figure 6.30 Comparison of the water levels for each simulation at point FI1

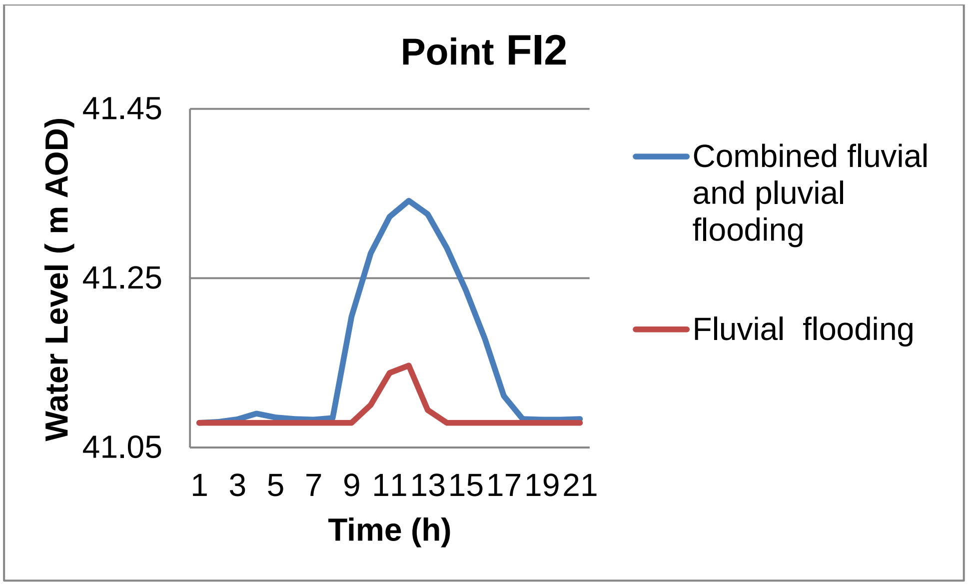

Figure 6.31 Comparison of the water levels for each simulation at point FI2

It can be seen in Figure 6.30 and in Figure 6.31 that the combined fluvial and pluvial flooding can cause higher water levels than only fluvial flooding can for the same point, and the same return period. The combined fluvial and pluvial flooding has a significant impact on the flood inundation area.

C.) Comparison of water depths (m) between combined and discrete flood events

The combined flood events with discrete flood events were compared in this section. Firstly, water depth was calculated from the summation of the water depth values of the same point from discrete pluvial and fluvial flooding (Figure 6.3). These discrete fluvial and pluvial flooding events were designed for the 1 in 100-year event. The methodology of the fluvial flooding can be found at the methodology section of Chapter 3. The methodology of the pluvial flooding can be found at the methodology section of Chapter 5. The water depth value of discrete events was named as Sum in the figures.

Secondly, water depth was calculated directly from the combined fluvial and pluvial flooding event simulation for the 1 in 100-year event. The methodology of the combined fluvial and pluvial flooding can be found in the methodology section of Chapter 6. This was named as Combination in the figures.

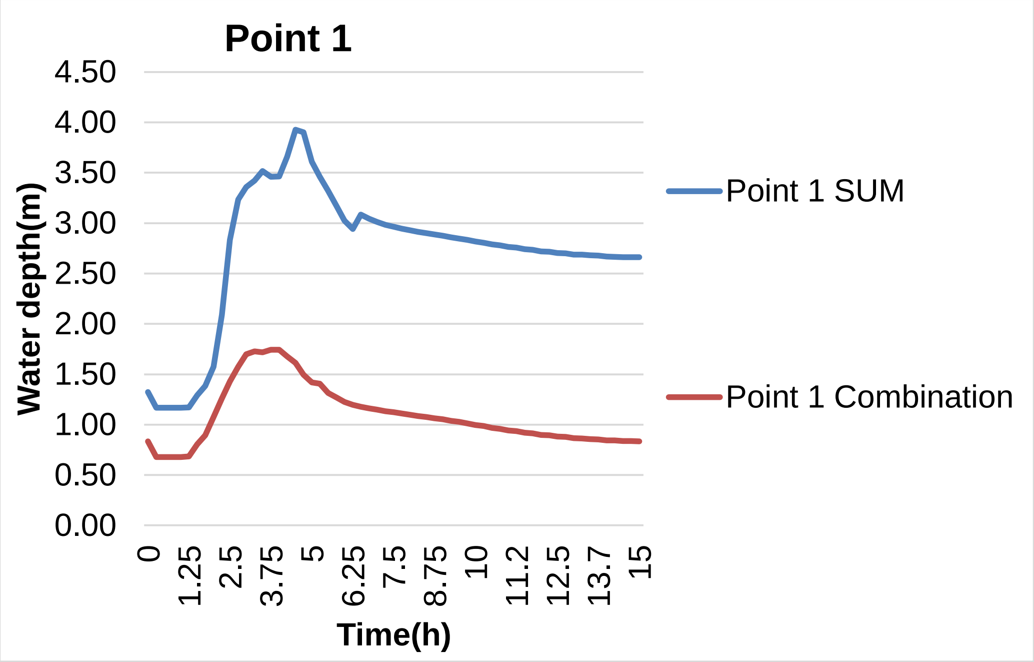

Figure 6.32 The water depth at Point 1

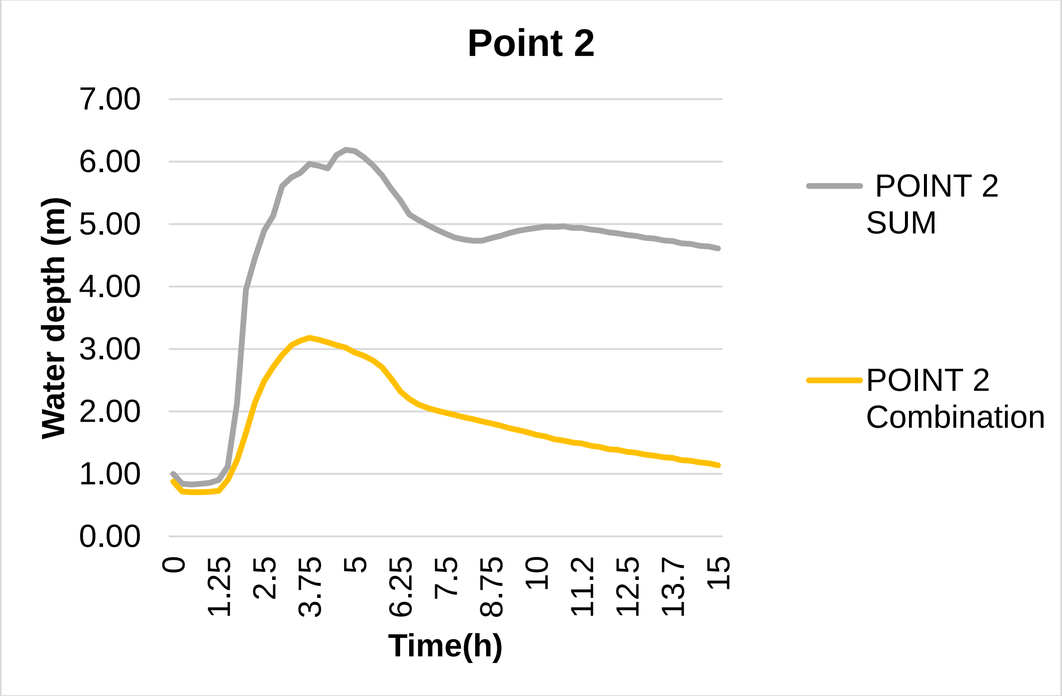

Figure 6.33 The water depth at Point 2

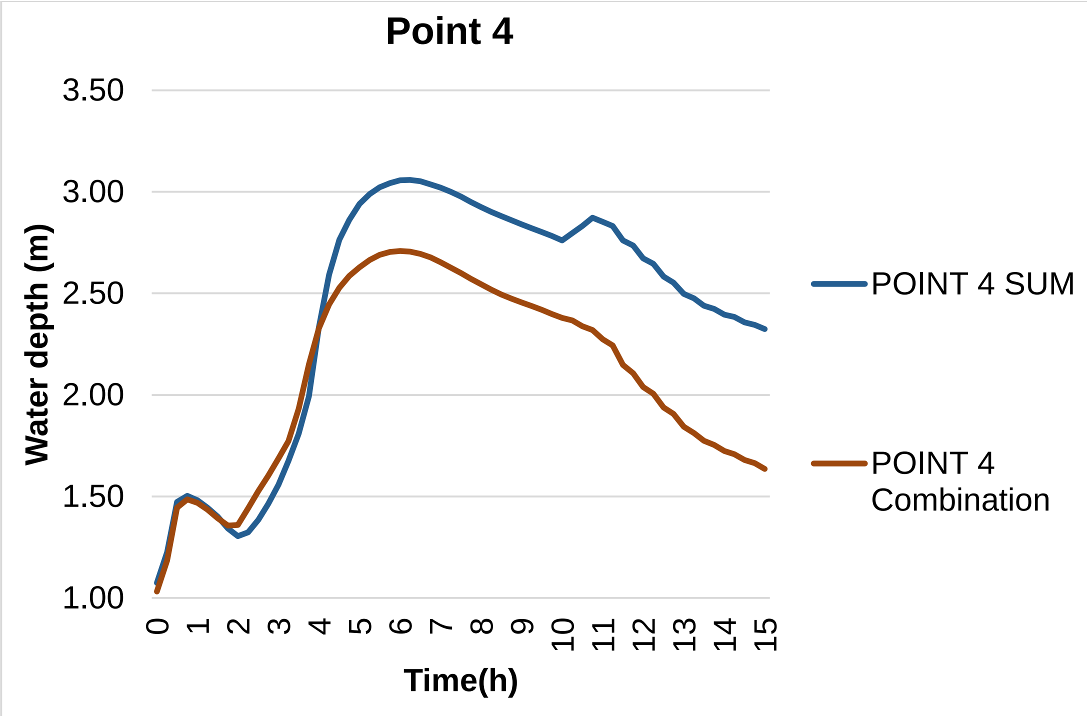

Figure 6.34 The water depth at Point 4

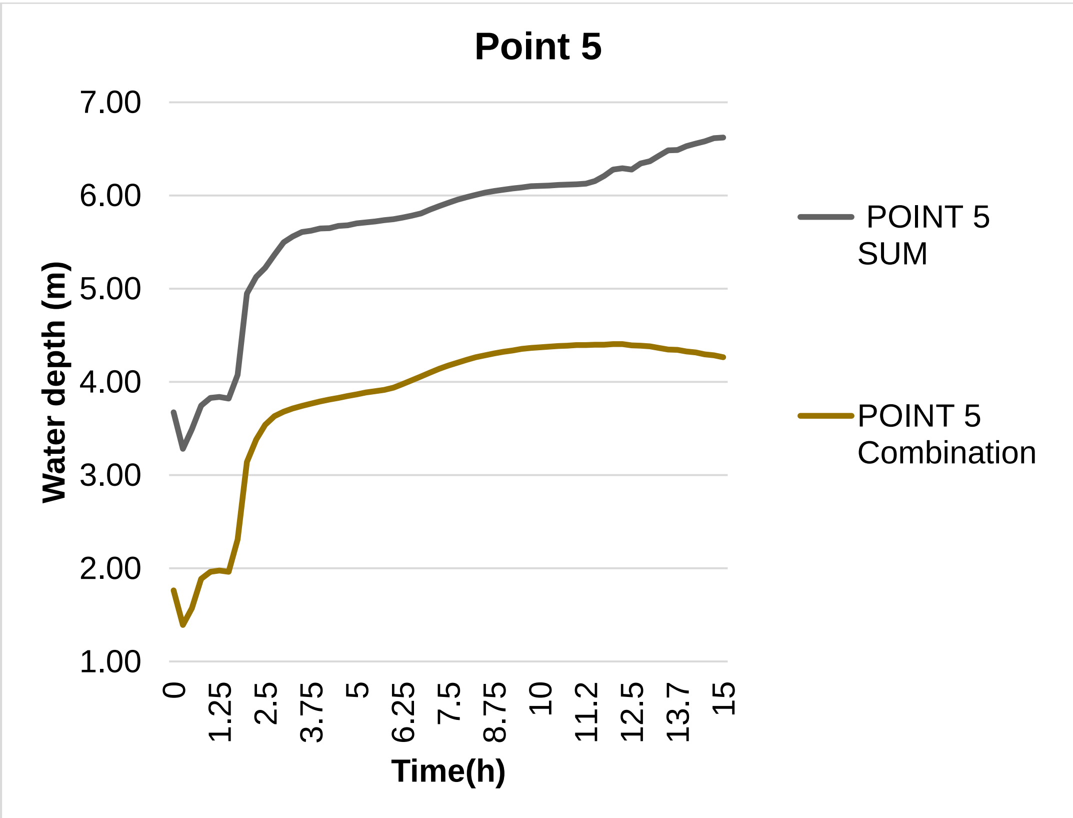

Figure 6.35 The water depth at Point 5

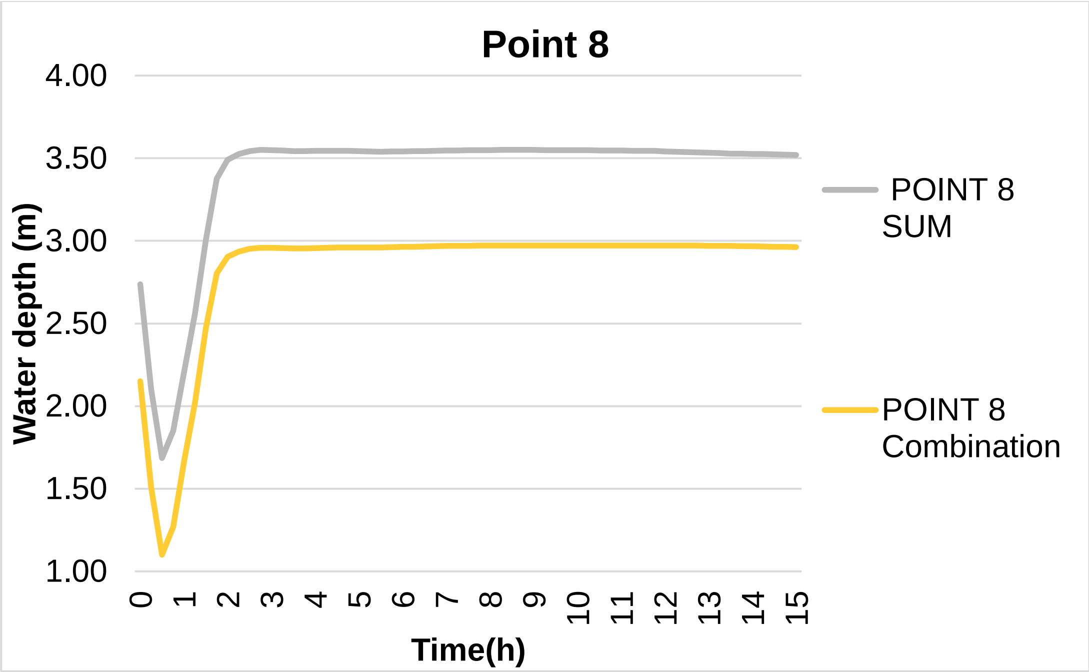

Figure 6.36 The water depth at Point 8

The discrete fluvial and pluvial flooding (Figure 6.14 and 6.15) was compared to the combined fluvial and pluvial flooding. The combined fluvial and pluvial flooding map (Figure 6.18) displays the flood extent and the water level of both river flow and rainfall.

Figures (from Figure 6.32 to Figure 6.36) display that water depth (m) from sum-up of independent fluvial and pluvial flooding is bigger than combined fluvial and pluvial flooding. The limit can be that the results from discrete flood events cannot indicate the sum of outcomes from the different flooding source directly. For instance, the water level of the fluvial and pluvial flooding at the same point in the flood extent cannot be summed directly. Therefore, to overlap the maps of discrete flood events is not realistic approach to observe the water depth of combined events. However, the combined pluvial and fluvial flooding can be displayed in the flood inundation area directly because this approach has both rainfall and river flow inside the model.

D.) Discussion of single event simulation and combined fluvial and pluvial events

The levels of the water level in the single event simulation and combined fluvial and pluvial flooding model can be seen in Figures 6.37 to 6.40 for the observation points (see Figure 6.3).

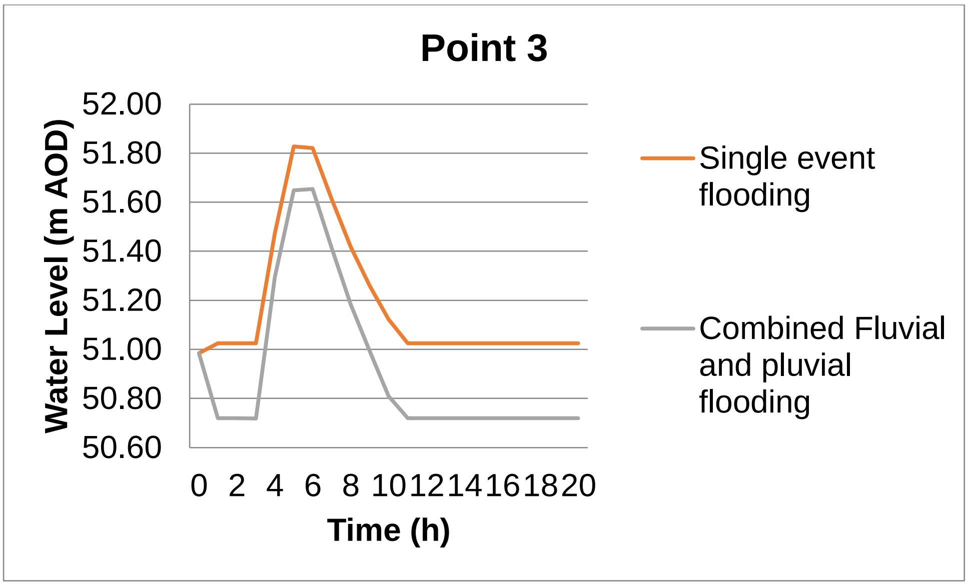

Figure 6.37 The water level at Point 3

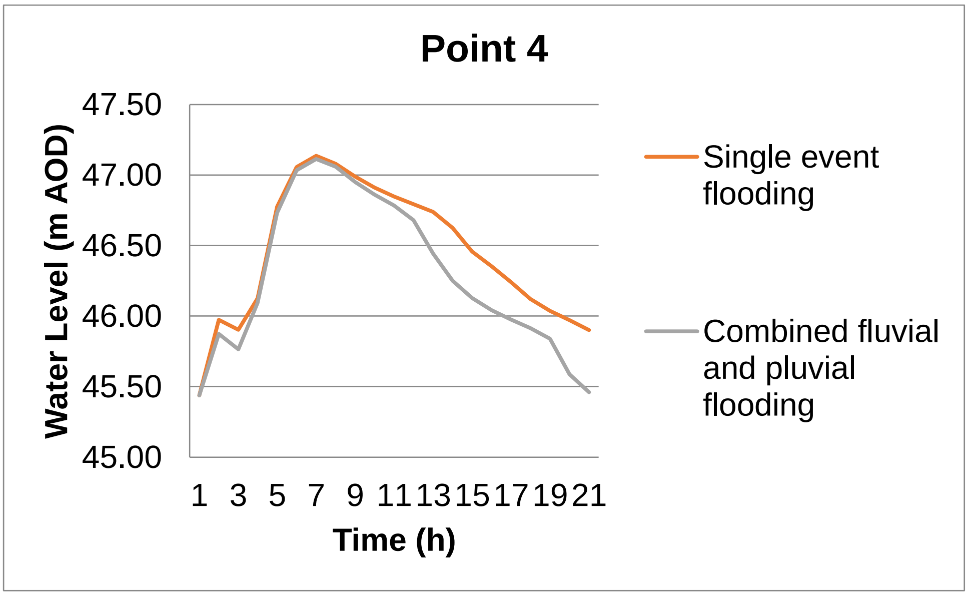

Figure 6.38 The water level at Point 4

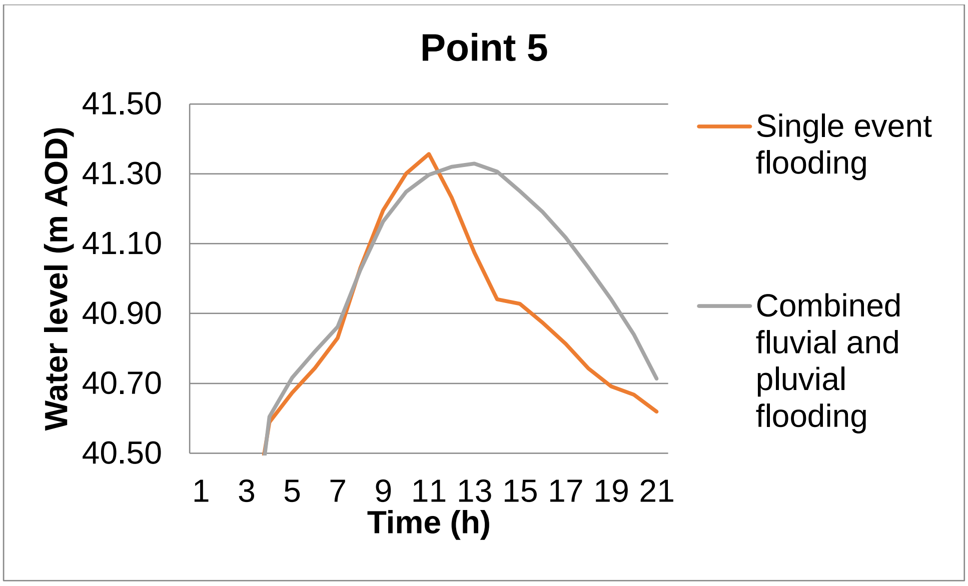

Figure 6.39 The water levels at Point 5

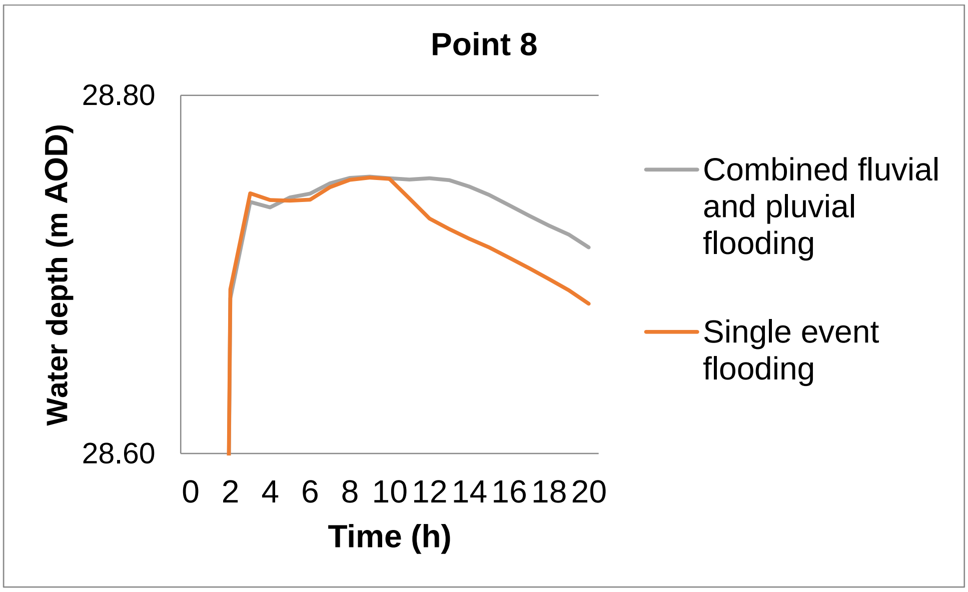

Figure 6.40 The water levels at Point 8

The water levels of the single event simulation are almost similar with the combined of fluvial and pluvial flooding for the points, except point 3 in Figure 6.37. The reasons are likely to be that lateral flow is effective at this particular point, the peak flow could have been calculated high, and it was applied as constant value during the single event simulation. In addition, rainfall event was applied only on the Lower Wortley Beck area in the combined simulation.

This assessment presented comparisons of combined fluvial and pluvial flooding with the only fluvial flood, with the single event simulations and with discrete flood events.

The important outcomes of the assessments are that

1. Single event simulation displays higher water levels than fluvial flooding because of the impact of the peak flow at the outfall of the New Farnley sub-catchment to the river channel.

2. The water levels from the fluvial flooding are higher than from those for the pluvial flooding. However, the values of the pluvial flooding virtually became closer to the water levels of the fluvial flooding. This could mean that rainfall-runoff process of the pluvial flooding takes more time due to the runoff being slower and longer.

3. There are some limitations of only overlapping discrete fluvial and pluvial flooding maps. Firstly, water levels of the same points in the flood extent area of fluvial flooding and pluvial flooding cannot be aggregated directly. Secondly, flood extent of the combined sources cannot be presented accurately. Lastly, the impact of combined water depth on the flood extent cannot be observed.

The dependence of the fluvial and pluvial flood events can be investigated by assessing sufficient long time series of river flow and rainfall data or by utilizing a large-scale weather generator and a hydrological model (Apel et al., 2015; Breinl et al., 2015). The peak water level in river channels, also the timing and the duration of local rainfall events are critical to examine the fluvial and pluvial flood inundation. To assess the dependency of the fluvial and pluvial flood events, the rainfall duration, catchment respond time, and land use materials can be the primary concerns. However, the analysis of combined fluvial and pluvial events would increase the computational time (Apel et al., 2015).

In summary, to evaluate the flood risk of the combined fluvial and pluvial flooding, flood level and extent of the combined events, rainfall-runoff and river flow should be combined in the model, and during the simulation. Thus, the combined fluvial and pluvial flooding can be observed on the floodplains directly.

6.4 Conclusion

Pluvial and fluvial flood events are usually investigated discretely. The interdependency of pluvial and fluvial flooding in an urbanised stream basin was discussed in this chapter. The interaction point between pluvial and fluvial flooding was determined as the floodplains of urban streams in this research. The fluvial flooding can be seen because of the overflow urban streams, and pluvial flooding can be seen because of the impermeable surfaces on the floodplains by these streams. Lower Wortley Beck area is an example of this link between the fluvial and pluvial events on the floodplain.

The aim of this research was to observe combined pluvial and fluvial flooding on the floodplains, to aggregate floodwater from both river overflow along the river channel and surface runoff on the floodplains by the river. The combined fluvial and pluvial flooding was simulated by using the 1D river channel link with the 2D direct rainfall model for the Lower Wortley Beck area. This approach enables both rainfall and river flow within the model as such demonstrates the simulation of pluvial and fluvial flooding on the floodplains. Thus, the flood extent with the water depth of the combined fluvial and pluvial flooding on the floodplains of the Lower Wortley Beck can be simulated and observed. Maximum water depth, water levels, and common flood inundation areas from combined fluvial and pluvial flood events were produced and examined. The Lower Wortley Beck area is suitable for this research because there is both fluvial flood risk and pluvial flood risk by the Lower Wortley Beck due to the area by the stream is urbanised. This approach was used for the Lower Wortley Beck area, but this approach can be applied to other urban stream basins. Lastly, the outcomes confirmed that the combined flooding could be more dangerous than single flood event, to analyse flood events separately can cause to underestimate the flood risk and only overlapping the flood inundation maps cannot display the realistic flood extents and depth values.

Chapter 7 Conclusion

7.1 Introduction

Urban flooding is a significant risk all over the world because the adverse effects of flood events on society and economy. In addition, process, magnitude, and length of the flood events have many uncertainties. When all of these factors are considered, to enrich the approaches of the urban flood risk assessment and management used by National and Local Governments are necessary.

In this research, to enrich the approaches of the urban flood risk assessment, the effects of rainfall events (rainfall duration), land use changes (urban developments, SUDS), and return periods (AEP) were analysed on flood risk in urbanised catchments. In addition, combined pluvial and fluvial flooding on the floodplains of urban stream basins was investigated. The interdependencies of flood processes were defined, and their interactions were viewed on the floodplains. The consequences of the combined flooding can be severe because the magnitude of their combined effects can be larger. However, the studies of combined fluvial and pluvial flooding are very rare.

The area for this research is the Wortley Beck catchment, in the South West of the City of Leeds, UK. Wortley Beck catchment is an ungauged and urbanised catchment. Fluvial and pluvial flood events were modelled by using hydrological and hydrodynamic models. The simulation results confirmed that the site has a severe level flood risk from both pluvial and fluvial, specifically, between Gelderd Road and the Ring Road area. The reasons for food risk of this area could be both the lack of culvert capacity and Farnley Reservoir. This research area is important because new settlements are expected to be built in the flood zone.

Chapter 3 presents the fluvial flood model of the Lower Wortley Beck in this research. The Revitalised Flood Hydrograph (ReFH) model was used to estimate the inflows from Farnley Beck and Farnley Wood Beck sub-catchments. 1D (Flood Modeller Suite) linked with the 2D (TUFLOW) fluvial hydrodynamic model. The effects of the sub-catchments were assessed on fluvial flood risk of the Lower Wortley Beck, Leeds, UK.

Chapter 4 presents single event simulation. In this chapter, in addition to the inflow, lateral flow from New Farnley was integrated within the fluvial system of the Lower Wortley Beck. Lateral flow represents the peak discharge at the outlet of the New Farnley basin. Peak flow was estimated by using rational method. Therefore, surface overflow at the New Farnley was observed as discharge at the outfall of the basin. The peak flow was estimated by using different rainfall event and land-use scenarios. Single event simulation was performed to assess the effects of the peak discharge of the upstream sub-catchment on the fluvial flood risk at Lower Wortley Beck.

In Chapter 5 a pluvial urban flooding, caused by extreme rainfall intensities combined with impermeable surfaces, was modelled. As there is not sufficient recorded data in the Wortley Beck catchment, net rainfall hyetograph was estimated by using Revitalised loss model in the Flood Modeller Suite tool. 2D TUFLOW hydrodynamic model with direct rainfall approach was used to model pluvial flooding so that the relationship between rainfall event and flood risk can be determined. The primary advantage of this method for an ungauged catchment was that flow values were computed from different design rainfall events.

Chapter 6 combined fluvial and pluvial flooding presents a methodology to assess the interaction between the pluvial and fluvial flooding on the floodplains of urban stream basins. Combined fluvial and pluvial flooding was examined on the floodplains in the Lower Wortley Beck area. Settlements in urban areas have increased specifically, on the floodplains. These settlements create impermeable surfaces so that an intense rainfall event can cause pluvial flooding in the Lower Wortley Beck area.

In addition, due to urbanisation and high-intensity rainfall events, fast discharge can be observed from the sub-catchments of Wortley Beck. Thus, fluvial flooding can be observed at the Lower Wortley Beck area.

The methodology was used to combine inflow hydrographs of the sub-catchments of Wortley Beck catchments and net rainfall hyetograph of the Lower Wortley Beck area. This approach was developed specifically, for this part of Leeds but this method can be applied to other cities in the world.

Overall, the results were produced for various return periods, land use and rainfall event scenarios to display the flood depth and flood extents. The flood extents were displayed by using the probabilistic flood inundation maps.

Key contributions of the project are that,

1. This research reviewed and updated the hydrological and hydraulic assessments of the Wortley Beck catchment. Hydrological assessment of the fluvial floods system was updated by using the ReFH rainfall-runoff model. The fluvial model was calibrated by using measured rainfall and water level data in this research.

2. The rational method has been used to design the urban drainage system. However, the rational method was used to calculate the maximum discharge to display the surface runoff of the upstream basin in this research. Thus, the impact of peak flow on the fluvial food risk at the downstream locations could be assessed.

3. Urban pluvial flooding was modelled by using the direct rainfall modelling approach rather than the traditional rainfall-runoff models.

4. Flood frequency was investigated for the ungauged catchments by computed discharge for any location in the catchment by using direct rainfall-runoff model and pooled method.

5. This research provided an approach that can be used to assess combined fluvial and pluvial flooding in urbanised catchments and displayed their interaction on the floodplains.

Key findings of the project are that,

1. The rainfall intensity, duration, and ratio, location of the impermeable surface area in sub-catchments can influence the flood magnitude and arrival time.

2. The overflow of the upstream basin has a significant impact on the flood risk of the downstream location. Therefore, land use change, the capacity of drainage system and rainfall duration of the upstream area should be considered to manage flood risk at the downstream area.

3. The results indicated that rainfall return period is not always the same as the flood return period.

4. Combined flood events can have larger flood extents and depths than a single type of flood event. This information could be used to develop further flood damage mitigation approaches.

However, there are some limitations of this research. For instance, urban drainage system data of the Wortley Beck catchment could not be provided in this research. A continuous loss can be integrated into the pluvial flood modelling. There were not sufficient measured flow data to estimate flood events from the measured data directly. In addition, there were not sufficient historical flood records of Wortley Beck catchment.

Further work is required to improve the methodology of combined fluvial and pluvial flood events. The peak time and duration of the rainfall event and flooding should be considered. This approach can be enriched by analysing the catchment response time. To improve the results of the simulations of fluvial and pluvial flooding, small grid resolution can be used.

New settlements should be avoided building in the flood-prone areas. In addition, some flood resilience approaches can be used to manage the surface runoff. In these places, sustainable urban drainage systems should be used, such as, permeable surfaces in car parks or green roofs. Flood risk assessment should regularly be conducted and updated. Innovative research approaches can be adapted to the urbanised and ungauged catchments.

The outcomes of this research can be used to enhance the flood resilience approaches to mitigate the adverse flood consequences of flooding in urban areas by the insurance agencies, stakeholders, urban planners, and local government agencies.

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