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Assessment of The Impact of The Ratio of The Developed Area on The Fluvial Flood Risk of Lower Wortley Beck

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Abstract

Population and valuable investments have been increasing day by day in basins. Thus, urban rives create a serious potential risk in the cities. This paper investigates the impacts of the percentages of the impermeable surfaces on the discharges from sub-catchments of the Lower Wortley Beck, Leeds, UK. Lower Wortley is in urbanized and ungauged part of the basin. The fluvial flood events were created by combining hydrological and hydrodynamic models for various events. Flood events were designed by using Revitalised Flood Hydrograph (ReFH) rainfall-runoff models. The impact of land use changes was examined by applying various Extent of urban and suburban cover (URBEXT) parameter of the Flood Estimation Handbook (FEH) catchment descriptor. Also, flood extents were simulated by linking Flood Modeler Suite with TUFLOW, hydrodynamic models. The outcomes of these simulations are probabilistic inundation maps with maximum water depth values. Thus, the impact of the different percentages of the impermeable surfaces of the sub-catchments on the discharge and fluvial flood risk at the downstream can be observed. These outcomes can be used to enrich the flood resilience approaches by city councils.

Keywords: Probabilistic Fluvial Flood Risk Assessment, Urban Rivers, Land Use Change, URBEXT.

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1. Introduction

Fluvial flood can be the most significant natural threat all over the world [1, 2, 3]. In addition, urbanization can alter the size of a flood event by increasing surface runoff and decreasing the catchment response time [4]. Thus, intense discharge at the outfall of sub-catchment can affect the downstream flood size [5]. Especially, the rivers in the developing basins can be directly influenced by the land use change in a sub-catchment [6].

The aim of this research is to investigate the influence of the percentage of the impermeable surface on the discharge and fluvial flood risk at the downstream [7]. The research focuses on the Lower Wortley, Leeds, UK. Firstly, The Environment Agency flood zone map displays that this area is in flood zone 3 where has a 1 in a 100 year or higher risk of fluvial flooding [8, 9]. Secondly, the Lower Wortley Beck are affected by discharges of the sub-catchments of the Wortley Beck which are Farnley and Farnley Wood. The discharges of sub-catchments of the Wortley are combined at the Lower Wortley. Thirdly, there is a culvert in here. The culvert can cause backwater effect in this location [8]. Lastly, the consequences of a fluvial flood event in this location can affect directly transportation links between the M621 and A6110. This area has been undergoing urbanization [10] so the consequences of flood events will be much serious also, an updated assessment of the probability of the flood events in this location is necessary to manage the future flood risk for Wortley Beck catchment.

In this paper, the impact of the land use on the fluvial flood risk was analyzed by investigating the influence of the percentage of impermeable surfaces on the discharge from the outlet of the sub-catchment. Firstly, the impact of the land use change was analyzed by using different Extent of urban and suburban cover (URBEXT) parameter values in this research.

The impact of the extent of catchment urbanization has always been considered for assessment of the flood frequency and catchment response times [4]. Initially, an Ordnance Survey (OS) 1:50,000 scale map was used to define the urban and suburban areas in the catchment in 1975, then digital Land Cover Map of Great Britain (LCMGB) was produced by the CEH Monks Wood [4]. However, in 1990, satellite imagery was used to define urban and suburban land cover data. This data was used to derivate the URBEXT1990 values for calculations of the Flood estimation handbook [4].

Secondly, due to the Wortley Beck was an ungauged catchment therefore, the discharges of the sub-catchments of the Wortley Beck were estimated by applying an event-based flood estimation method. Guo and Adams recommended the event-based probabilistic model in 1998 [11]. Also, the event-based probabilistic models can be used to compute discharge for a specified return period in ungauged catchments [12]. These designed rainfall events can be integrated with a loss model and inserted into a flow routing model to simulate flood events [13, 14].

As a result of this, the designed discharges were integrated with a 1D/2D hydrodynamic fluvial flood model to assess the downstream flood risk in this research. The 1D/2D hydrodynamic fluvial flood software was Flood Modeler Suite link TUFLOW in this study. In addition to the 1D river channel model, a 2D solver is necessary to simulate the fluvial flood extent. Therefore, the Environment Agency investigated a 2D solver tool to link 1D Flood Modeller Suite. Two-dimensional Unsteady FLOW (TUFLOW) was one of the 2D solvers, producing reliable flood extents [15]. The link between the Flood Modeller Suite (CH2M) and the TUFLOW (BMT WMB) tools has been classified as suitable for simulations flood extents [16-19].

2. Material and Method

This research conducted an analysis of the impact of the land use change on the downstream flood risk. Thus, the effects of the ratio of the impermeable surfaces on outflow discharge of the sub-catchment could be examined. The Revitalised Flood Hydrograph (ReFH) rainfall-runoff Model and a one-dimensional Flood Modeller Suite link two-dimensional TUFLOW hydrodynamic model were used.

The probabilistic fluvial flood risk at the Lower Wortley due to the land use change was assessed by applying these following stages, first, as result of the Wortley Beck is urbanized and ungauged basin, to calculate inflow, Rainfall-Runoff method for the ungauged site was used. Discharges from sub-catchments into the Lower Wortley Beck were computed by using Revitalised Flood Hydrograph (ReFH) methods in Flood Modeller Suite framework [20]. Properties of the sub-catchments were found in the Flood Estimation Handbook CD-ROM 3. Second, the percentage of the impermeable surfaces in the catchment was examined by using the extent of urban and suburban land cover for a specific year (URBEXT). Putro also examined the impact of urbanization on the fluvial system by using URBEXT in 2013. URBEXT is a catchment descriptor parameter in the ReFH rainfall-runoff model of the Flood Modeler Suite. Different values of the URBEXT parameter were used to analyze the response of the sub-catchments to the urbanization by observing the change on the discharge and catchment respond time.

The Revitalised Flood Hydrograph rainfall-runoff model is a physically-based conceptual model [21, 22]. A loss model, routing model and a base flow model are the sub-models of the ReFH model. The ReFH rainfall-runoff Model can be used to generate flood events from designed rainfall by considering the concept of seasonal variation in soil moisture content [21]. Loss model is used to calculate net rainfall. The total flow of the catchment is calculated by adding the base flow [7].

Initially, to design the rainfall events, critical storm durations (D) of FB and FWB sub-catchments were calculated from Equation 1. Time to peak was calculated from equation 2. The catchment descriptor parameters of the equations were obtained from the FEH CD-ROM 3.0 [23] by using Easting-Northing coordinates of the sub-catchments (Table 1).

The Critical Storm Duration

$D = T_P(1 + \frac{SAAR}{1000})$, D = the Critical Storm Duration (h), TP = Time to Peak (1)

Time to Peak

$$T_P = 1.563 \times PROPWET^{-1.09} \times DPLBAR^{0.60} \times (1 + URBEXT)^{-3.34} \times DPSBAR^{-0.28} \quad (2)$$

Where at Equation 1 and 2;
DPLBAR: mean drainage path length (km)
DPSBAR: Mean of all the inter-nodal slopes for the catchment (m/km)
PROPWET: index of proportion of time that soils are wet
SAAR (mm): Standard Period Average Annual Rainfall (mm)
SPRHOST: Standard Percentage Runoff (%) derived using HOST classification
$URBEXT_{1990}$: FEH index of fractional urban extent for 1990 [24]; [22].

Table 1. Catchment descriptors of FB and FWB sub-catchments

	Area (km²)	$URBEX_{1990}$	SAAR	PROPWET	DPLBAR	BFIHOST	DPSBAR
FB	29.67	0.1704	799	0.33	5.85	0.449	75.3
FWB	20.95	0.2314	731	0.32	4.87	0.359	61.7

The undeveloped area and developed area of the sub-catchments;

$$Undeveloped\ Area = (AREA - (AREA \times URBEXT))$$
$$Developed\ Area = (AREA \times URBEXT) \quad (3)$$

The calculation of the area of the developed and undeveloped land cover of the sub-catchments of the Wortley Beck was calculated by using equation 3.

In addition to these calculations, to assess the impact of the ratio of urbanization on the fluvial flood risk, the ratio of the urban land cover in the sub-catchment was calculated for different scenarios [7].

Equation 4 was used to calculate the increase in the ratio of the developed area in the sub-catchment.

Urbanisation expansion factor (UEF) [25],

$$UEF = 0.8165 + 0.2254\ TAN - 1\{\frac{(YEAR - 1967.5)}{21.25}\} \quad (4)$$

Reducing the ratio of the developed area in the sub-catchment was the one other scenario in this study [7]. The rate of the developed area of the Farnley Wood Beck basin was decreased to the minimum rate. Kjeldsen (2009) mentioned that 30 % of a catchment could be the minimum rate of the developed area (Equation 5).

Total percentage imperviousness [26],

$$I = 30\%\ Urban = 30\%\ 2.05\ URBEXT = 0.615\ URBEXT \quad (5)$$

Third, probabilistic fluvial flood maps with maximum water depth (m) were produced by using Flood Modeller Suite link TUFLOW. The one-dimensional hydraulic model was used to simulate the river channel system of the Lower Wortley Beck was modelled by Flood Modeler Suite (v 3.7.0) software (CH2M HILL/Halcrow (UK)). Flood Modeller Suite software uses the finite difference method to solve the De Saint Venant Equation for the calculations of the unsteady flow. Flood extents of the Lower Wortley were modelled by linking TUFLOW (v 2013-12-AD- ISP-w64) in this study [7].

TUFLOW software was generated by BMT WBM. Also, the hydrodynamic model was linked to the geographic information system (GIS) tool to produce these maps by using LiDAR data.

The data sets of the hydraulic structures and initial conditions of the Lower Wortley Beck were taken from the Environment Agency. The Digital Terrain Model (DTM) data set was supplied at 8m resolution from the Environment Agency and the UK Ordnance Survey.

3. Results and Discussion

To assess the impact of the rate of the impermeable surface in the sub-catchment on the fluvial flood risk, firstly, the ratio of the developed area in the sub-catchments were computed.

Initially, $URBEXT_{1990}$ value of the of Farnley and Farnley Wood is 0.17 and 0.23, respectively. The impermeable surface of the Farnley and Farnley Wood is 5.06 km^2 and 4.8 km^2 respectively in the 1990 year.

For the first assessment, the ratio of the developed area in the sub-catchments was increased by calculating the Urbanization Expansion Factor for the year of 2016 (Equation 4). Thus, the rate of the urban land cover becomes greater than the year of 1990 for the sub-catchments.

The rate of the impermeable area of sub-catchments was calculated as 0.27 for the Farnley and 0.37 for Farnley Wood for the year 2016 [7].

For the second assessment, the ratio of the developed area in Farnley Wood Beck (FWB) sub-catchment was decreased to 0.15 by applying equation 5 [7]. The impermeable surface of the

Farnley Wood for the first scenario is 7.86 km^2 and for the second scenario is 3 km^2. The impermeable surface of the Farnley is 8.13 km^2 for the first scenario and the impermeable surface of the Farnley was not decreased for the second scenario due to the $URBEXT_{1990}$ value of the Farnley is already very small that is 0.17.

Secondly, catchment response time (time to peak (T_P)) and storm duration (D) of Farnley and Farnley Wood were calculated to estimate discharge [7].

Initially, the catchment response time of the Farnley and Farnley Wood sub-catchments are 2.7 h and 2.2 h respectively. Also, estimated rainfall duration values of the Farnley and Farnley Wood sub-catchments are 4.8 h and 3.8 h respectively.

For the first scenario, the catchment response time of the Farnley and Farnley Wood sub-catchments were computed by using Equation 2 Time to Peak and Equation 1 The Critical Storm Duration $URBEXT_{2016}$ values of the FB and FWB basins are 0.27 and 0.375 respectively. Catchment response time the Farnley and Farnley Wood sub-catchments are 2.0 h and 1.5 h respectively. The estimated rainfall duration values the Farnley and Farnley Wood sub-catchments are 3.6 h and 2.64 h respectively [7].

Next, Critical Storm Duration values were entered in the Flood Modeller Suite ReFH boundary framework and discharge hydrographs were designed (Figure 1).

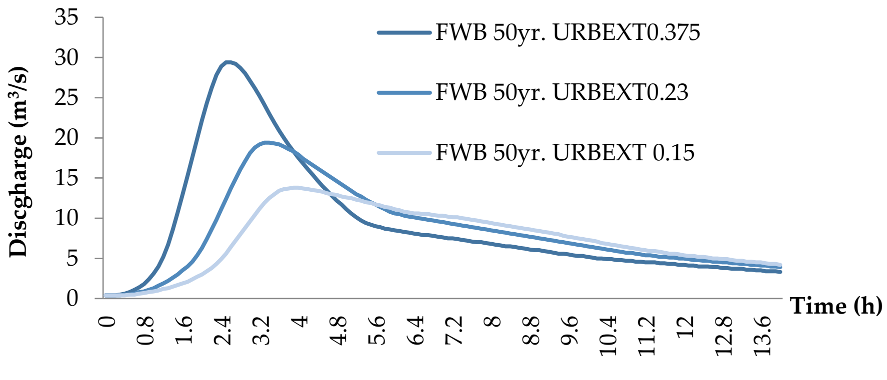

Figure 1. Discharge for a 2 % AEP on the upstream boundary

Peak values of the discharges from Farnley Wood Beck are 14 m^3/s, 19m^3/s, and 29m^3/s respectively for a 2 % AEP flood event. This can be seen from Figure 1 that when the ratio of the impermeable surface is increased catchment response time becomes greater but peak discharge becomes smaller [7].

Lastly, the discharges were entered into the 1D link 2D hydrodynamic model and fluvial flood extents were produced with maximum water depts (Figure 2) [7].

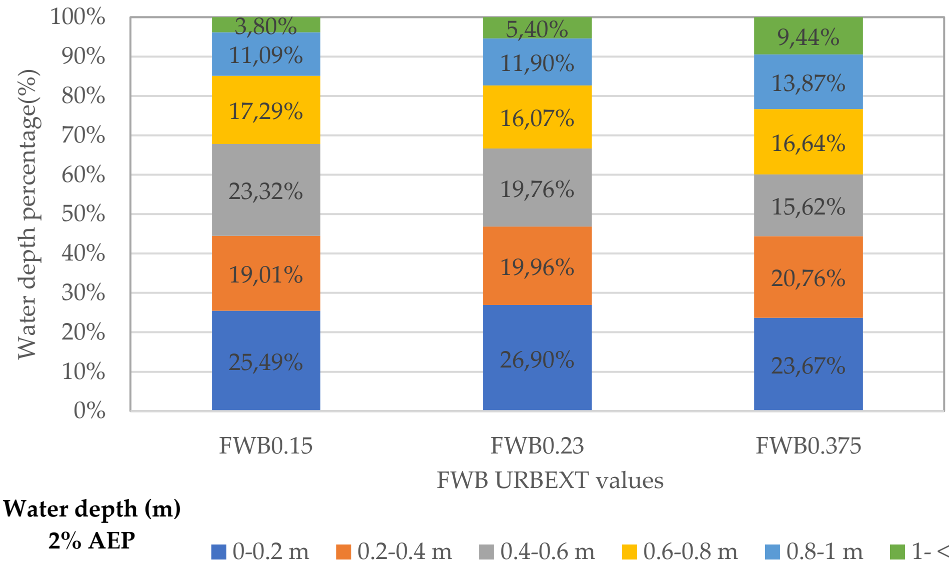

Figure 2. Water depth percentage (%)

This can be seen from Figure 2 that when the ratio of URBEXT increases, the flood depth can become greater.

The fluvial flood extent of a 2 % AEP flood event for initial conditions, which are each URBEXT values of Farnley and Farnley Wood are 0.17 and 0.23 respectively, is 0.26 km². The fluvial flood extent of a 2 % AEP flood event for the first scenario, which is the ratio of impermable surface is increased, each URBEXT values of Farnley and Farnley Wood are 0.27 and 0.37 respectively, is 0.28 km². The fluvial flood extent of a 2 % AEP flood event for the second scenario, which is the ratio of impermeable surface of Farnley Wood is decreased and the ratio of impermeable surface of Farnley was kept the same as the value of the URBEXT of the 1990 year, each URBEXT values of Farnley and Farnley Wood are 0.17 and 0.15 respectively, is 0.24 km²[7].

This could be said that when the ratio of URBEXT increases, the flood extent area can become greater.

The main limitation of this study is that only the ratio of the developed surface was changed. Miller et al., (2014) found similar outputs but Miller et al., (2014) stated that a simplification approach of land use change and land use properties cannot be sufficient to observe the catchment runoff [27]. Moreover, Kumar et al. (2017) and WMO and GWP (2008) added that the variety, location and amount of vegetation in the catchment are some of the important observation parameters due to the impact on the infiltration and evaporation in the catchment [28, 29].

4. Conclusion

The study assessed the impact of the ratio of the urbanized land on the catchment response, discharge, and fluvial flood risk at the downstream of the Lower Wortley. Lower Beck is an urban river channel along the developed lands with a high potential of fluvial flood risk. In addition, it is in the ungauged catchment. Therefore, discharge of the sub-catchments was calculated by using catchment descriptors to run ReFH rainfall-runoff model of the Flood modeller suite framework. The ratio of developed land was applied by using URBEXT parameter of the Flood Estimation Handbook (FEH) catchment descriptor. Then these dischargers were entered the 1D Flood Modeller suite link 2D TUFLOW hydrodynamic model. Fluvial flood extents at the downstream of the Lower Wortley Beck were produced with maximum water depth for different ratios of the developed land in the sub-catchments of the Wortley Beck.

The outputs of this study displayed that when the undeveloped area is transformed into the developed area, surface runoff on the developed basin can reach time to peak earlier and the size of the peak discharge can be greater. Also, downstream flood risk becomes greater due to the flood depth and flood extent can become greater.

In the future, this study can be extending by adding the location of the developed land, and the properties of vegetation in the rural area in the sub-catchments. Also, the results can be used to improve flood resilience approaches such a SuDS.

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