Advancing the Unit Flood Response Approach for Urban Flood Management

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The candidate confirms that the work submitted is his/her own, except where work which has formed part of the jointly authored publications has been included. The contribution of the candidate and the other authors to this work have been explicitly indicated below. The candidate confirms what appropriate credit has been given within the thesis where reference has been made to the work of others.

Each chapter has either been published or is currently under review for publication. As such the four publications which form the main body of work in this thesis are outlined below, along with the contributions of each author.

The work in **Chapter 2** of this thesis has appeared in publication as follows:

Singh, A., Dawson, D., Trigg, M., & Wright, N. (2021). A review of modelling methodologies for flood source area (FSA) identification. *Natural Hazards*, *107*, 1047-1068.

Singh A developed the structure and the contents of the publication as well as revised the contents after review. All literature was searched and was reviewed by Singh A, additionally, all images and tables were also produced by Singh A. Where images cite other authors, permission was granted to use the image. All co-authors contributed to the discussion, structure and organisation of the manuscript.

The work in **Chapter 3** of this thesis is currently under review:

Singh, A., Dawson, D., Trigg, M., Wright, N, Willis, T. *under review*. Evaluating the unit flood response approach using 2D rain on grid modelling. Journal of Flood Risk Management.

Singh A collected the data required for the modelling, and solely built the hydrological, meteorological and topographic inputs to the models. The structure, contents, and analysis of the manuscript were also conducted by Singh A. Additionally, all postprocessing was conducted by Singh A, using GIS suits and Python. All co-authors contributed to the discussion, structure, and organisation of the manuscript. Willis, T., assisted with the initial set up of the TUFLOW models. BMT provided the licenses for TUFLOW and hence have been listed in the acknowledgments.

The work in **Chapter 5** of this thesis has been accepted for publication as follows:

Singh, A., Dawson, D., Trigg, M., Wright, N., Seymour, C., & Ferriday, Pu*blished.* Application of the Capacity Assessment Framework for Drainage Representation in Urban Flood Models. Journal Of Hydrology

Singh A developed the methodology on the use of the dataset provided by Yorkshire Water and conducted the modelling for the three case studies. This includes data collection of all key inputs such as generating the rainfall inputs, topographic inputs, and land use data, and setting up the model runs. All postprocessing was conducted by Singh A using GIS, Python and Excel. Additionally, the structure, contents, and analysis of the manuscript were also conducted by Singh A. Seymour C and Ferriday L provided the capacity assessment framework dataset. All co-authors contributed to the discussion, structure, and organisation of the manuscript.

Abstract

Flooding is the most frequent natural disaster that causes significant, societal, economic, and environmental damage. The processes involved in flooding are shaped by spatial and temporal factors including weather patterns, topography and geomorphology. In urban setting, where landscapers are dynamic, land cover, green spaces, and drainage play a crucial role. Recognising flood source areas (FSAs) is pivotal for strategic flood risk management (FRM). Although FSA identification is not novel concept, recent advancements in flood modelling research, driven by technology and methodology improvements have extended beyond traditional methods. Emerging modelling approaches in FRM propose innovative methodologies for flood risk mitigation focusing on understanding and addressing flooding at its source.

This thesis offers a review of current modelling approaches used to identify FSAs, specifically the Unit Flood Response (UFR) approach. The approach is a spatial prioritisation method for flood defences and mitigation. Traditionally, reliant on hydrological modelling and streamflow routing, this these instead uses rain-on-grid models (TUFLOW and HEC-RAS 2D) to assess the importance of model choice for the UFR approach for a catchment in the UK. The thesis further developed the UFR methodology by using a Hazard Index (HI) and Building Exposure Index (BEI) to show the significant differences between the model outputs, as well as emphasising on the computational costs associated with these methodologies.

Additionally, recognising the important role of drainage systems in urban infrastructure, this thesis addresses the limited body of work available on drainage representation in flood models by introducing the Capacity Assessment Framework (CAF) to be used for drainage representation. By applying the CAF to assess and represent the drainage system in Leeds, the thesis draws a direct link between spatial prioritisation of flood defences and drainage system performance. The thesis introduces the application of the CAF outputs in flood models, demonstrating a more explicit representation of spatially varied drinage capacity. By comparing the national average removal rate (NARR) of 12 mm/hr with CAF-derived rates, the significant of realistic drainage representation in flood models is highlighted.

Lastly, the UFR approach coupled with 2D rain-on-grid modelling is used to investigate the impact of climate change and drainage representation in the Lin Dyke catchment. This approach considers three scenarios (Baseline, Baseline+Climate Change, and Baseline+Climate Change+Drainage) to establish hazard and building exposure indices. Results highlight the importance of incorporating climate change projections and drainage representation in the UFR methodology for a thorough urban flood risk assessment.

In synthesis, this thesis investigates the multiple factors of flood risk management, offering insights and innovations across various dimensions. The Unit Flood Response (UFR) emerges as promising tools for identifying flood source areas (FSAs), emphasising the need for adaptive decision-making in flood risk management (FRM). Our investigation extends beyond affected areas, focusing on understanding, and addressing flooding at its source. Moreover, the introduction of the Capacity Assessment Framework (CAF) provides a novel methodology for representing drainage systems in flood models based on their realistic performance in urban environments. By incorporating realistic representations of spatially varied drainage capacities in flood models, this thesis highlights the importance of considering multiple factors in the assessment for effective urban flood risk management. As climate change and urban development exert increasing pressures, the findings in this thesis underscore the importance of integrating these factors into flood risk models to ensure resilience and relevance in the face of evolving challenges.

Dedication and Acknowledgements

My PhD process has been challenging but also enjoyable even in the face of a global pandemic. I could not have reached the end if I did not receive constant support and encouragement from my supervisors Dr. David Dawson, Prof. Mark Trigg, and Prof. Nigel Wright. Special thanks to Prof. Mark Trigg who has bettered my research curiosity and confidence in all aspects since my Masters. I cannot thank you enough for inspiring the confidence in me to execute this project. I cannot thank you enough for always providing me with opportunities that go beyond my PhD. I would also like to thank all of my friends, family and my dog Ricky for supporting me through the PhD.

Acknowledgement must go to the University of Leeds, for providing me with the opportunity to pursue this PhD and trying their best to accommodate students during the pandemic. Thanks to Engineering and Physical Sciences Research Council for funding this project. I wish to thank Duncan Kitts from BMT for his special contribution to the project and for being incredibly accommodating with TUFLOW licences for myself and the University of Leeds. Special Thanks to Yorkshire Water for providing me with the all the necessary data sets for this project. I also want to thank Alex Fionda from WSP for his input on the Wortley Beck model and being extremely responsive and patient with all my queries. I must also thank Leeds City Council for showing interest in the project and engaging with me and my supervisors. This project was a collective effort and could not have been completed if it wasn’t for the key inputs provided by Duncan Kitts, Luke Ferriday and Alex Fionda.

I thank you all for your overwhelming support.

Declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award.

Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

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List of Abbreviations

Abbreviation	**Definition**
ADA	Adaptation Driven Approaches
ANN	Artificial Neural Networks
ARR	Australian Rainfall Runoff
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
BEI	Building Exposure Index
BGI	Blue Green Infrastructure
BLCC	Baseline Climate Change
BLDRCC	Baseline Drainage Climate Change
BMP	Best Management Practises
CAF	Capacity Assessment Framework
CC	Climate Change
CMIP	Couple Model Intercomparison Project
CN	Curve Number
CPU	Central Processing Unit
CSO	Combined Sewer Overflows
CSV	Comma separate values
DEFRA	Department for Environment Food and Rural Affairs
DEM	Digital Elevation Model
DPLBAR	Drainage Path Length
DPSBAR	Mean Drainage Path Slope
DTM	Digital Terrain Model
DWE	Diffusive Wave Equation
DWF	Dry Weather Flow
DWMP	Drainage and Wastewater management plans
EA	Environment Agency

ETU	Elementary Territorial Unit
FAS	Flood Alleviation Scheme
FDM	Finite Difference Method
FEH	Flood Estimation Handbook
FEM	Finite Element Method
FI	Flood Index
FREM	flood risk evaluation method
FRM	Flood Risk Management
FSA	Flood Source Area
FSR	Flood Studies Report
FVM	Finite Volume Method
GA	Genetic Algorithm
GCM	Global Climate Models
GIS	Geographical Information Systems
GPU	Graphic Processing Unit
HEC-HMS	Hydrological Engineering Centre Hydrological Modelling System
HEC-RAS	Hydrological Engineering Centre River Analysis System
HH	High High
HHR	Hydrological homogenous regions
HI	Hazard Index
HL	High Low
HPC	High Performance computing
HRU	Hydrological Response Units
IPCC	International Panel Climate Change
LCC	Leeds City Council
LH	Low High
LID	Low Impact Development
LiDAR	Light Detection and Ranging

LL	Low Low
LLFA	Lead Local Flood Authority
LSA	Local Spatial Autocorrelation
LULC	Land use land Change
NARR	National Average Removal Rate
NFM	Natural Flood Management
NRCS	Natural reserve conservation service
NS	Navier Stokes
OS	Ordnance Survey
PDE	Patial Differential Equations
RCM	Regional Climate Models
REFH	Revitalised Flood Hydrograph
RMA	Response Matrix Approach
RoSWF	Risk of Surface Water Flooding
RR	Rainfall-Runoff
SOMFCM	Self-organising feature maps and fuzzy c-means
SOTER	Soil and Terrain Digital Database
SPR	Source Pathway Receptor
SUDS	Sustainable urban drainage systems
SVE	Saint Venants Equation
SWE	Shallow Water Equation
SWMM	Storm Water Management Model
TSR	Time Series Rainfall
UCA	Unit Cell Approach
UDS	Urban drainage system
UFR	Unit Flood Response
UKCP	UK Climate Projections
VSA	Variable Source Areas
WRMP	Water Resource Management Plans
WSUD	Water Sensitive Urban Designs

WWTP	Wastewater Treatment plant

Chapter 1 Introduction

Flooding threatens the UK's residential homes, businesses, and critical transport infrastructure. For example, the December 2013 and March 2014 flooding in the UK resulted in economic damages of ~£1,300 million in England and Wales. Residential properties account for 25% of this damage, followed by businesses (Fenn et al., 2016). Additionally, the 2015 to 2016 floods following the passage of Storm Desmond and Eva resulted in economic damage of £1.3 billion to £1.6 billion (Environment Agency, 2018). Before 2012, flooding across nearly half the UK caused 1.2 billion in costs, with pluvial flooding contributing significantly to these losses (Hynes and Hirsch, 2012). Undoubtedly, the most damaging flood event occurred in 2007, which caused ~£3.2 billion in economic cost. Along with severe monetary damages, flooding also causes significant disruption to livelihood local and national services. For instance, the 2015-2016 and 2007 flooding events caused substantial harm to schools, primary transport links, national infrastructure, and energy supply (Chartteron et al., 2016).

The severe impacts of flooding have led to increased investment in flood defences, whereby 1,500 flood defences will benefit from £2.3 billion in funding by 2021 (Defra, 2015). However, this funding prioritises areas recently affected by flooding, and applying schemes to current high-risk regions may prove economically inefficient (Vercruysse et al., 2019a). Significantly, considering climate change projections and future urban growth may alter hydrological and geomorphic processes and, thus, the source and receptors of flooding (Stevens et al., 2016; Coles et al., 2017). Therefore, areas currently deemed high-risk, or flooding hotspots may not be classed as such in the future (Stevens et al., 2016; Vercruysse et al., 2019a; Maghsood et al., 2019). While efforts have been made to improve flood mitigation and management within the UK, it remains fragmented, failing to adapt urban areas to the threat of flooding (Kundzewicz et al., 2010; Lhomme et al., 2013; Houses of Parliament, 2016), mainly due to data and modelling challenges that hinder from understanding flood risk holistically.

Flooding is a costly natural disaster, and its frequency, magnitude and cost are expected to increase due to factors such as population growth, urbanisation, and climate change (IPCC, 2014; Watts et al., 2015; Pregnolato et al., 2017; Lowe et al., 2019; IPCC, 2022). Urbanisation, particularly, alters the natural landscape, leading to the construction of built environments and grey infrastructure such as buildings and roads (i.e., buildings, roads, bridges, etc.) (Waters et al., 2003; Falconer et al., 2009; Darmanto et al., 2019). The expansion of urban areas and the subsequent increase in grey infrastructure have reduced the capacity of infiltration, surface retention and interception, all processes that help reduce the flow of flood waters (Miller et al., 2014; Fletcher et al., 2015; Miller and Hutchins, 2017; Butler et al., 2018). Flooding remains a critical challenge within the UK;

paramount to this challenge is addressing the issue of adapting urban cities to the threat of increased flood risk (Charlton and Arnell, 2014; Fenner et al., 2019; O'Donnell and Thorne, 2020)

Key to this task of adapting cities is the concept of flood resilience or resilient cities, which requires detailed comprehension of flood processes on a large spatial and temporal scale (Hallegatte, 2009; Balsells et al., 2015; Lamond et al., 2015; Zevenbergen et al., 2017; O'Donnell et al., 2019; Browne et al., 2021). Hydrodynamic models provide the opportunity to understand flood processes. However, their use is currently limited to predefined scenario testing. It is adapting urban cities to the threat of current and future flood risk that is driven by adaptation rather than allocating resources to emergency responses and local-scale flood contingency plans. Instead, the transformation of urban cities to flood risk should be caused by an approach that systematically targets areas that both consider areas of high flood impact and regions that contribute significantly to this impact (Saghafian and Khosroshahi, 2005; Vercruysse et al., 2019b; Rodriguez et al., 2021). Therefore, it leads to a systematic framework that underscores the "whole catchment" approach and promotes flood management holistically.

Over the past decade, there has been a significant shift in the methods employed for flood risk management (FRM) (O'Donnell and Thorne, 2020). This change has been driven by recognising the need for a comprehensive understanding of the processes involved in flood risk, emphasising flood prevention and protection as essential components in addressing the issue. Consequently, approaches such as Natural Flood Management (NFM) and sustainable urban drainage systems (SUDS) have emerged as leading strategies for tackling flooding. These NFM and SUDS solutions adopt a holistic approach to flood risk, offering numerous benefits in addition to flood mitigation (Jato-Espino et al., 2016; Ghofrani et al., 2017; Lashford et al., 2019; Ferguson and Fenner, 2020; Yang and Zhang, 2021; Wu et al., 2023). Typically, these solutions are implemented as source control measures to reduce runoff into areas prone to flooding, as indicated by impact maps. However, there is currently a lack of guidance on efficiently implementing these solutions through modelling techniques (Saghafian, 2005; Petrucci et al., 2013; Saghafian et al., 2015).

Managing floodwater at its source and minimising flood risk in critical locations, such as within urban areas, is becoming increasingly crucial in FRM and flood modelling (Makropoulos et al., 2001; Saghafian et al., 2008; Petrucci et al., 2013; De Vleeschauwer et al., 2014; Fletcher et al., 2015). Consequently, researchers are revisiting the concepts of Vulnerable Source Area (VSA) analysis to aid in identifying the sources of flooding and guiding integrated FRM using more comprehensive approaches and methodologies. These studies can be referred to as Flood Source Area (FSA) identification approaches, explicitly aimed at determining the most effective ways to locate the primary sources of flooding across a catchment area, thereby enhancing preventative management practices. Methods of flood source area identification, such as the unit flood response (UFR) approach, drive methodologies that aim to investigate areas within a catchment that contribute significantly to flooding (Saghafian et al., 2008; Sulaiman et al., 2010; Singh et al., 2021). The UFR methodology (**Figure 1-1**.) provides a framework to improve urban flood resilience by spatially and systematically identifying areas that would benefit the most from flood intervention. However, despite its recent uptake in research, there remain critical gaps in the development and application of the approach for FRM; the following section outlines these gaps.

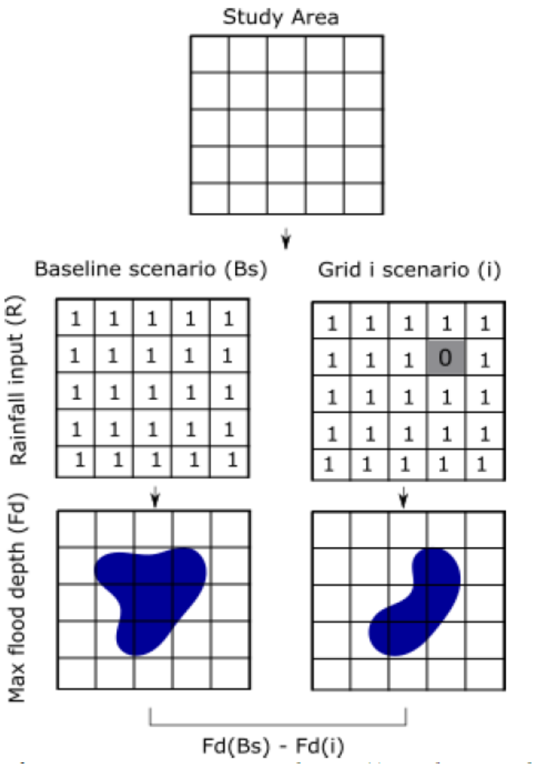

Figure 1-1: Procedural diagram for source-to-impact analysis: (i) study area divided into cells; (ii) uniform rainfall applied to generate flood depth maps; (iii) cell dependency analysis performed by omitting rainfall from a cell at a time; (iv) subtract flood depths

1.1 Background

Traditional flood modelling combines hydrology and hydraulics to simulate and analyse the processes of river and water flow during flood events. This involves utilising hydrodynamic models to represent the movement of water and a hydrological model to generate floodwater propagation. This helps understand and manage flood risk in rivers and floodplains (Teng et al., 2017; Nkwunonwo et al., 2020). **Figure 1-2**. provides a summary of critical numerical solutions, solvers and schemes used for hydrological and, more importantly, hydraulic modelling.

The hydrological element of the model incorporates water-related processes such as rainfall, evaporation, infiltration, and runoff. Within flood modelling practises hydrological models estimate the volume and timing of runoff generated from rainfall events. Hydrological models can be lumped, semi-distributed and fully distributed, referring to the complexity in which the spatial parameters of the catchment are represented (Wheater, 2002; Pattison and Lane, 2011; Miller et al., 2014). Lumped models assume a catchment has uniform descriptors such as catchment area, soil type, land use, slope and precipitation data to predict a hydrograph for a given rainfall event within a catchment (Ghavidelfar and Reza, 2011). Semi-distributed hydrological models assume some spatial variability within the catchment and, therefore, divide the catchment into smaller hydrological response units, e.g., the Soil and Water Assessment Tool (SWAT) (Welde, 2016). Fully distributed hydrological models such as the Hydrological Engineering Centres-River Analysis System (HEC-RAS) subdivided the catchment into cells, and each cell is represented individually with its own set of hydrological parameters(Beven*, 2001; Götzinger and Bárdossy, 2007). The hydrograph generated from the hydrological models represents the amount of water that flows into a river system and is utilised as an input for hydraulic modelling. Figure 1.2. provides examples of standard numerical solutions for lumped, semi-, and fully distributed hydrological modelling. Integrated hydrology and hydraulics are crucial in flood modelling to accurately represent flood events. Hydrological models provide inflow hydrographs, which are used as inputs into hydraulic models (Kjeldsen, n.d.). The hydraulic models then use the hydrographs to simulate the spatial distribution of flooding both as river flow and overland flow on a floodplain (Dawson et al., 2008; Chang et al., 2015a; Aksoy et al., 2016). Sections three and four within this Chapter provide further detail on the mathematical principles of hydraulic models.

Modelling fluvial floods usually involves generating a discharge hydrograph for a single event using a rainfall-runoff hydrological model (Wheater, 2002; Pattison and Lane, 2011; Miller and Hutchins, 2017). In urban areas, pluvial floods are frequent occurrences; pluvial flooding is caused by rainfall that accumulates on the ground, leading to flooding and ponding before the water can enter any watercourse or drainage system (Pina et al., n.d.; Houston et al., 2011a; Pina et al., 2016; Bertsch et al., 2017a; Lashford et al., 2019; David and Schmalz, 2020; Wu et al., 2023). In some cases, the water may not be able to enter the drainage network because the system is already at total capacity, resulting in localised flooding within the urban environment. Integrating hydrological and hydraulics for flood modelling provides a comprehensive understanding of flood behaviour within a catchment and its impact on local communities and infrastructure (Leandro et al., 2009a; Haghighatafshar et al., 2018).

1.1.1 Fundamentals

The shallow water equations (SWE) are a set of partial differential equations (PDEs) used to model water flow behaviour in river channels and flood plains during flood events. To derive the SWE, the

Navier-Stokes equations (NS), which govern the motion of viscous fluid under certain assumptions and simplification, are reduced to SWE (Neelz et al., 2010; Kundzewicz et al., 2010; Roberts et al., 2015; Teng et al., 2017; Costabile et al., 2021; Bates, 2021):

The final form of the SWE can be written as two partial differential equations:

1. The Continuity Equation (Mass Conservation Equation):

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0$$

Equation 1

Where h is the water depth, u is the velocity in the x-direction, v is the velocity in the y-direction, and t is time.

2. The Momentum Equations (x and y directions):

$$\frac{\partial (hu)}{\partial t} + \frac{\partial (hu^2)}{\partial x} + \frac{\partial (huv)}{\partial y} + gh\frac{\partial h}{\partial y} - \tau x = 0$$

Equation 2

$$\frac{\partial (hv)}{\partial t} + \frac{\partial (huv)}{\partial x} + \frac{\partial (hu^2)}{\partial y} + gh\frac{\partial h}{\partial y} - \tau y = 0$$

Equation 3

Where g is the acceleration due to gravity, τx and τy are the bed shear stress components, and huv represents the product of water depth and the velocity in the corresponding direction.

The SWE equations can be further approximated based on the dominant terms in the equations and the simplifications required. Three main approximations of the SWE are commonly reported in the literature (Bates and De Roo, 2000; Uhlenbrook et al., 2004; Khan et al., 2009; Cea et al., 2010; Bates et al., 2010; Neal et al., 2011; Fewtrell et al., 2011; Bout and Jetten, 2018), they are:

1. The diffusive wave approximation, which neglects the inertial terms in the SWE.
2. The kinematic wave approximation neglects both the inertial and pressure gradient terms within the SWE. It is commonly used for fast flows regulated by downstream water levels and the channel/bed slope.
3. The inertial wave approximation only considers the inertial terms in the SWE.

1.1.1.1 Numerical Methods

Solving SWE is computationally challenging and demanding, mainly when complex flows over a large domain. Hence, various numerical methods are used to compute the solutions for SWE. These are:

1. Finite Difference Method (FDM): Divides the domain into a grid of discrete points in space and time, representing water depth and velocity. Used in flood models, FDM suffers from stability issues and requires fine grids for accurate fast flow capture (Wasantha Lal, 1998; Syme et al., 2004; Kundzewicz et al., 2010).
2. Finite Element Method (FEM): This technique uses an irregular mesh of interconnected finite elements, often triangles or quadrilaterals, covering the domain (Bates and De Roo, 2000; Mason et al., 2003; Aronica and Lanza, 2005).
3. Finite Volume Method (FVM): FVM divides the domain into cells, treating them as containers for flow variables. SWE are integrated over cells, and fluxes at cell boundaries determine flow in and out. (Glenis et al., 2018; García-Feal et al., 2018; Hou et al., 2020; Hariri et al., 2022).

The schemes used to implement these numerical methods can be implicit or explicit; the choice depends on the simulations' stability and accuracy requirements. Implicit solvers, for instance, are stable but computationally costly, whereas direct solvers are more computationally efficient (Wasantha Lal, 1998; Bates and De Roo, 2000; Teng et al., 2017; Hou et al., 2020; Webber et al., 2021).

1.1.1.2 Types of Models

As previously mentioned, 1D, 2D and 3D models are commonly used in hydrodynamic models to simulate flooding. 1D models focus on simulating water flow within river channels and piped systems. It uses 1D Saint-Venant equations (SVE) to represent the conservation of mass momentum between two cross sections apart in the x-direction along the river reach. 1D models are computationally efficient and ideal for simple river systems. They help provide information about water depth, velocity, and discharge along the river's longitudinal profile. 2D models can represent flow over flood plains and low-lying areas adjacent to river channels. In contrast to 1D models, 2D models solve the full 2D versions of the SWE equations considering depth and lateral flow movement. Hence, they can capture the spatial variations of floods over complex topography and provide more accurate simulations for flooding in urban areas (Mark et al., 2004a; Sto. Domingo et al., 2010; Teng et al., 2017; Li et al., 2020; Nkwunonwo et al., 2020; Bates, 2021). Lastly, 3D models are used for highly detailed and complex structures, as they model flow in all three spatial dimensions and consider both horizontal and vertical flow movements. Although 3D modelling provides the highest level of detail, it is not commonly used due to extensive computational demands.

One-dimensional (1D) and two-dimensional (2D) hydrodynamic models are commonly used in flood modelling. 1D models are used to simulate flows within river channels and piped systems, while 2D models are used to represent flows over floodplains and other low-lying areas. Coupled with 1D-2D models, these models can be linked together, simulating flooding considering the river channel details and overland flow. Couple 1D-2D models are widely used for flood risk assessments, floodplain mapping and FRM strategies to mitigate the impact of flooding(Leandro et al., 2009b; Bazin et al., 2014; Hammond et al., 2015; Yu et al., 2016; Teng et al., 2017; Haghighatafshar et al., 2018).

1.1.1.3 Rain-on-Grid

In recent years, rainfall has been directly applied using models to simulate non-fluvial flood risk. This approach is known as direct rainfall modelling or rain-on-grid (RoG), where the hydrology and hydrodynamic flood processes are modelling in a single 2D hydrodynamic system (Zeiger and Hubbart, 2021; Costabile et al., 2021; Costabile et al., 2022; Hinsberger et al., 2022; Hariri et al., 2022; Godara et al., 2023). There are several reasons for the application of this method, the most common one being that it is known that fluvial flooding, which occurs when water levels in a river rise and riverbanks are overtopped, is not the only method of flooding, especially in urban areas (Houston et al., 2011b; Pina et al., 2016; Bertsch et al., 2017a; Coles et al., 2017). Additionally, it integrates hydrological and hydraulic processes in a single 2D model, thus simplifying the process and eliminating the need for separate models.

The traditional split between modelling hydrology and hydraulics was driven by limited computational capabilities, hence the two processes were treated separately. The historical approach to modelling was often lumped, providing a simplified representation of river flow, and 1D river channels modelled the hydraulics. Advancements in technology, and the availability of 2D data such as LiDAR, improved computational power such as the use of parallel computing and graphical processing unit (GPU)-based computing have transformed flood modelling by enabling the integration of 2D flood plain modelling with 2D distributed hydrological models (Mark et al., 2004a; Guidolin et al., 2016; García-Feal et al., 2018; Ming et al., 2020). Due to the improvement in methods and technology, various forms of flooding beyond riverine floods are now addressed. This includes pluvial floods in urban areas, which were previously challenging to manage due to data availability and methodology limitations. Continuous efforts to improve modelling methodology and technology have equipped researchers and practitioners to handle a broader range of flooding scenarios more accurately and efficiently in complex environments. This extension of high-resolution data sets and improved computing power allows the inclusion of floodplains and backwater events for storm hazard analysis within large study areas.

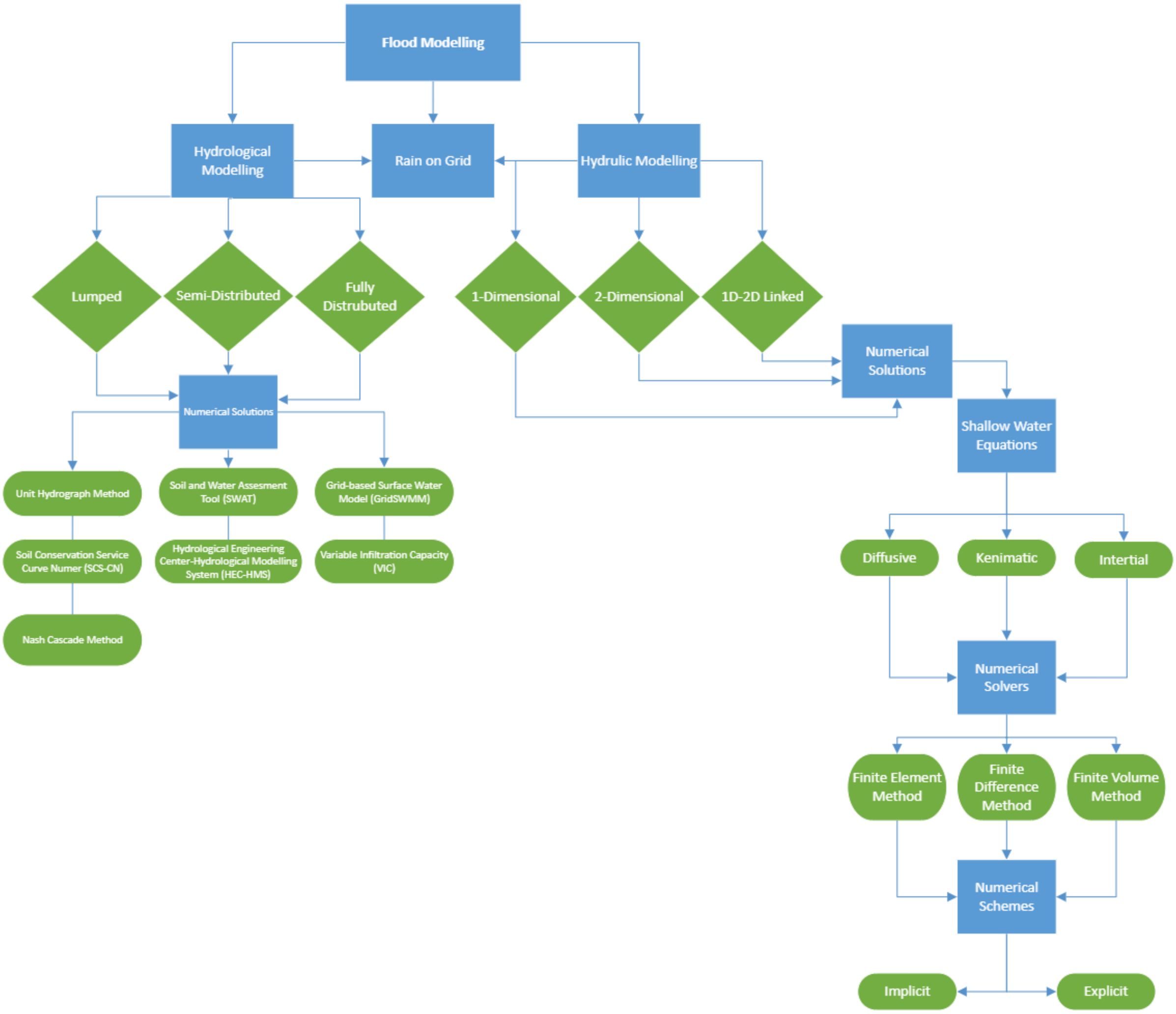

Figure 1-2: Overview of hydrological and hydrological modelling solutions, solvers, and schemes

1.1.2 Unit Flood Response (UFR)

The UFR approach is a modelling framework utilised to assess flood risk and identify significant source areas contributing to flood risk. The method was initially implemented for flood risk assessment and is based on the unit response matrix approach (RMA) principles used in petroleum engineering and groundwater modelling. The RMA was used to optimise oil production and analyse drawdown curves of oil wells. In groundwater modelling, it quantifies the effects of sink/source rates on the design variables at specific locations (Lee and Aronofsky, 1958; Aronofsky and Williams, 1962; Gorelick, 1983; Saghafian, 2005). The UFR approach's application in flood risk consists of four key steps. These are:

1. Subdividing the study areas into smaller areas termed as “units”.
2. Identifying the baseline flood risk within the study area

3. Conducting a sensitivity analysis where the hydrology within each unit is omitted; this procedure has been termed “cell dependency analysis” by Vercruysse et al. (2019) and will be referred to as unit dependency analysis within this thesis.
4. Using the results from the unit dependency analysis to generate a Flood Index (FI), which ranks the units based on their contribution to overall flood risk within the study area. The FI can be calculated using either equation 1 or equation 2.

$$FI_n = \frac{Q_{bs} - Q_s}{Q_{bs}} \, x \, 100$$

Equation 4

$$fi_n = \frac{Q_{bs} - Q_i}{A_i}$$

Equation 5

FIn is the gross flood index of the sub-catchment in percentage (%); Qbs is the baseline peak discharge generated at the outlet (in m3/s) with all the sub-catchments in the simulation. Q_s is the peak discharge at the outlet when *s* sub-catchment (in m^3/s) is omitted from the simulation. In equation 5, fi_n is the flood index of the *n* sub-catchment based on the sub-catchment area (in $m^3/s/km^2$), and *Ai* is the sub-catchment's area (in km^2).

The UFR approach is a systematic and effective means to identify flood source areas (FSAs) that contribute the most to impact zones. This makes it a valuable tool for optimising the implementation of source control measures within FRM strategies (Vercruysse et al., 2019a; Rodriguez et al., 2021; Webber et al., 2021). Like traditional flood risk assessment, the UFR approach can use various hydrology and hydraulic models to identify FSAs. Existing studies, however, have been limited to the use of hydrological models such as Hydrological Engineering Centre – Hydrological Modelling System (HEC-HMS) and Soil and Water Assessment Tool (SWAT), and hydraulic models such as HEC-RAS (Saghafian et al., 2010; Sanyal et al., 2014; Dehghanian et al., 2019; Maghsood et al., 2019). Only one study, to date, makes use of RoG modelling. However, the application of the 2D RoG model is limited to a small study area of 9 km2 (Vercruysse et al., 2019a). Table x summarises the types of models that have been used to apply the UFR approach to date.

Although various models are commonly used to assess flood risk in urban and rural environments, their applicability to the UFR approach remains unexplored, even though the need to identify FSA in a forever-changing climate and landscape is becoming more critical. A notable gap exists in applying the UFR approach using 2D RoG models. Unlike traditional stream-routing models that focus on well-defined river channels and model detailed flow within the river network, 2D rain-on-grid models allow the simulation of thin layers of runoff typical in urban catchments. Incorporating 2D RoG models into the UFR approach will address the limitations of traditional stream routing models, such as their inability to capture interactions between river channels and surrounding topography and poor representation of non-linear processes such as flood plain conveyance and backwater effects.

1.1.2.1 Objective 1

The 1st objective of this thesis is to conduct a comparative investigation of how different models, such as TUFLOW and HEC-RAS, identify FSAs. Achieving this objective offers valuable insights into the sensitivity of model choice and its implication for using the UFR approach and flood risk assessment. Therefore, the primary research questions to be addressed to achieve this objective are:

(i) Do models identify the exact source areas when applying the UFR approach (i.e., are priority source areas consistently identified independently of model choice)?
(ii) Are there correlations between urban spatial parameters and the source areas identified by the models?
(iii) To what extent do the identified source areas vary when using different models?

While single-model applications using stream-flow routing and hydrological modelling have demonstrated the usefulness of the UFR approach, they do not provide insights into the trade-offs between different models that are currently considered state-of-the-art or the advantages of varying modelling solutions and codes in identifying Flood Source Areas (FSAs), especially in urban areas.

Urban areas were previously challenging to manage due to data availability and methodology limitations. Continuous efforts to improve modelling methodology and technology have equipped researchers and practitioners to address a broader range of flooding scenarios more accurately and efficiently in complex environments. This extension of high-resolution data sets and improved computing power allows the inclusion of floodplains and backwater events for storm hazard analysis within large study areas.

1.1.2.2 Urban drainage systems, Climate Change and the UFR approach in flood risk assessment.

1.1.2.2.1 Representation of drainage systems

Urban areas heavily rely on drainage systems as essential infrastructure due to the dynamic interplay between anthropological activities and the natural water cycle. In a natural environment undisturbed by structures such as roads and buildings, natural methods of drainage would occur through infiltration of water into the ground, evapotranspiration, or conveyance from watercourses (Mark et al., 2004b; City et al., 2014; Martins et al., 2018). Reduction in natural ground cover due to increased urbanisation significantly affects these processes. Introducing artificial surfaces through an increase in grey space amplifies the volume of surface runoff compared to functions such as infiltration and, consequentially, increases the total volume and velocity of water reaching rivers. Over time, drainage systems have advanced from a simple ditch or gully on the side of a path to a complex network of underground pipe systems (Rodriguez et al., 2012; Ochoa-Rodríguez, 2013). One of the primary purposes of the drainage network is to direct excess runoff from built areas to a nearby watercourse or storm tanks located in treatment plants; this is also known as a stormwater drainage system.

During a storm event, a layer of run-off (overland flow) forms from intense rainfall and flows along streets and allies (urban surface pathways). Eventually, runoff flows to a watercourse or a gully where it meets the underground pipe system. Drainage infrastructure is designed to deal with a set capacity because it involves finding a compromise between the probability of a flooding event and the system's expected performance. Designing drainage systems to deal with rare, high-magnitude flood events will be economically impractical; therefore, the expected performance of the system is the level of flood risk it can provide under typical conditions (Rodriguez et al., 2012; Ochoa-Rodríguez, 2013; Jato-Espino et al., 2016).

In urban areas, on average, drainage design capacity can manage 12 mm/hr (Zoppou, 2001; Butler et al., 2018; Wang et al., 2018). Once the drainage system has reached capacity, it can no longer accommodate incoming runoff, leading to surcharge (overflow of water onto the surrounding streets when the drainage system's capacity has exceeded.), resulting in ponding and pluvial flooding. Although the pipes themselves may have sufficient power, the hydraulic capacity of gullies (openings in the ground found along streets) and manholes may limit the intake of the runoff volume (Mark et al., 2004b; Djordjević et al., 2005; Ochoa-Rodríguez, 2013). Therefore, a storm event more significant than the system design capacity will result in excess runoff.

As growth in population and hence housing/urban creep is increasing, urban drainage systems and their inability to address increased flood risk pose one the most significant environmental challenges in the UK (Chatterton, J ; Clarke, C;Daley, 2013; Fenn et al., 2016; Pregnolato and Dawson, 2018). Although engineered to replace natural drainage somewhat, drainage systems introduce a range of environmental and engineering challenges by affecting the hydrological response of an area (Jacobson, 2011; Hamel et al., 2013; Miller et al., 2014). Greenfield runoff rates are the storm/rainwater runoff in undeveloped areas with permeable surfaces (e.g., soil and vegetation). Although greenfield run-off rates are used to design drainage systems in new developments, they may not adequately incorporate an increase in frequency and intensity in extreme events due to climate change or poor functionality of ageing drainage infrastructure(Arnbjerg-Nielsen et al., 2013; Fenner et al., 2019).

As urban areas undergo further development, the increase in impermeable surfaces alters the natural flow of water, leading to drainage incapacity and surcharge resulting in pluvial flooding, which has the potential to change flooding locations. Furthermore, overland flow from sewer surcharge can increase the flow velocity and quantity, increasing flooding extent and water depth (Huang et al. 2008). Subsequently, the increase in runoff volume may result in high river flow magnitude, increasing the threat of river flooding (Hawley and Bledsoe, 2011). Pluvial flooding has also been linked to increasing the reoccurrence of small, localised floods (Braud et al., 2013).

To accurately simulate flood risk in urban areas, it is vital to represent urban drainage systems, as it significantly influences the accuracy of outputs from flood modelling (Leandro et al., 2009b; Leandro et al., 2016). However, the controlling factor in accurate urban flood modelling is the availability of drainage infrastructure data and the time taken to model the systems explicitly. Therefore, assumptions regarding drainage network capacity are often made when modelling urban flood risk (Hénonin et al., 2015; Vercruysse et al., 2019b). In most cases, the function of the drainage system is represented by simply subtracting a constant rate of rainfall – with the assumption that this is managed efficiently by the drainage system. Some studies that have used this constant rate include (Wang et al., 2018), when modelling flood risk in urban areas, applied a fixed reduction of 12 mm/hr to the design rainfall to account for drainage capacity. This is also practised within the industry; for example, the EA flood map for England and Wales applied a 30% reduction in their design rainfall before input into model simulations to represent drainage and infiltration within urban areas (Wang et al., 2018). Vercruysse et al (2019) conducted source-to-impact modelling and applied a drainage capacity estimate to model a 1:50-year flood event for Newcastle-upon-Tyne. The modelling exercise produced flood risk maps that identified source areas that contributed significantly to flood hazards in an urban domain.

While the outputs from studies that model urban flood risk with drainage capacity estimates aid in identifying locations susceptible to overland flooding, they perform poorly regarding flood processes and fail to represent catchment response during a flood event accurately. For example, studies that based their simulation on such assumptions have reported their results to under and over-predict flood depths and extents (Chang et al., 2015b; Webber et al., 2019). Furthermore, results also indicate discrepancies in the rate at which a catchment responds (Guerreiro et al., 2017; Wang et al., 2018). The issue with assuming to account for the drainage system in urban pluvial flood modelling is that often the source of the hazards is blockage in gullies and inlets or surcharging of manholes, and these are not represented when just applying a rainfall removal rate (Ten Veldhuis, 2010; Walsh et al., 2012).

Many studies have utilised the rainfall reduction approach to represent urban drainage and infiltration (Chen et al., 2009; Ahilan et al., 2014; Chang et al., 2015a; Hénonin et al., 2015). To tackle data unavailability, innovative methods such as synthetic generation of urban drainage networks have been developed to minimise the use of assumptions and estimates. Möderl et al. (2009) generated various virtual urban drainage systems (UDS) using the length of the UDS and slope of the catchment as inputs. The study yielded 10,000 virtual UDS, evaluated using performance indicators for surface flooding. The results indicated that virtually generated UDSs accurately reflected the performance of drainage systems in the real world. Betsch et al. (2017) used a GIS routine to generate synthetic storm drain inlet locations for urban flood modelling. The routine used OS MasterMap topographic data and generated 376 artificial storm drain inlets. The results showed that the representation of storm drain inlets is critical in areas that suffer from surface water flooding.

Furthermore, Li et al. (2020) developed the inlet-drainage approach that represents drainage losses as a mass subtracted in areas with gullies and inlets in China. The impact of the inlet drainage approach was investigated using hydrodynamic models for an idealised and actual case study. The results indicated that the system provided an excellent alternative to estimating drainage capacity in flood models. While the methodology has provided satisfactory results for urban flood modelling and is gaining traction, case studies related to synthetic drainage systems are still limited for it to be deemed a conclusive method to utilise without drainage data. For urban flood modelling, continued efforts must be made to improve drainage representation in urban flood models, mainly because drainage systems alter flooding pathways and routes in an urban environment.

The drainage system's capacity is varied; in certain areas, the drainage infrastructure may be well-designed and able to manage stormwater runoff efficiently. However, in some areas, the capacity may be inadequate or poorly designed, leading to limited efficiency in handling stormwater, resulting in surface ponding and localised flooding (Yu et al., 2016; Luo et al., 2022). The poor drainage performance in such areas is often exacerbated by due to impermeable surfaces in urban areas. The spatial variation in drainage capacity is due to several factors, such as the age and design of the drainage systems, the topography of the land, the presence of natural waterways or wetlands, and the extent of urban development.

Using a uniform value to represent the drainage capacity in urban areas neglects this spatial variation in the drainage system's ability. When assuming the drainage systems operate at a set capacity for the whole of the catchment, the underlying assumption is also that the system works at full potential—neglecting completely the impact of operational faults such as blockages, pumping station regimes, surcharges, and pipe capacity exceedance where pipes are designed for a smaller event. Additionally, this does not consider the local differences within the drainage system. By their nature, storm drainage systems also change the flow paths through an area, so for a complete understanding, drainage systems need to be present in models.

Understanding the spatially varied drainage capacity of the system is essential for effective flood risk management and urban planning. Identifying areas with inadequate drainage and assessing their vulnerability to flooding can guide the implementation of targeted drainage improvement projects and the development of appropriate stormwater management strategies. The ability to represent drainage infrastructure provides accurate and realistic outputs and improves understanding of flooding in urban areas. Often limiting the representation of drainage infrastructure is the availability of drainage data (Yu et al., 2016; Chen et al., 2020). Drainage data is usually unavailable due to several reasons depending on the location. Within the UK, drainage systems in different areas are managed by other entities such as the local council, water companies and private developers. Hence, collecting and managing this data is fragmented among various organisations. Furthermore, drainage data contains sensitive information such as infrastructure details or property boundaries; in these cases, the protection of privacy and security drives the limited availability of the data for public use and research.

1.1.2.2.2 Objective 2

This lack of drainage data challenges flood risk modelling and the UFR approach. Inaccurate representation of the drainage data has the potential to misidentify FSAs and impact zones. Hence, addressing the research gap related to the representation of drainage infrastructure in models is crucial for improving flood risk management in urban areas. In the context of the UFR approach, incorporating drainage information in models can enhance the identification of FAS and prioritisation of units. Therefore, the 2nd objective of this thesis is to develop a methodology for representing drainage systems in flood models. The primary research questions to be addressed to achieve this objective are:

(i) How can we represent the spatial variation in the drainage system's capacity in flood models?

(ii) What is the impact of representing drainage systems in flood models?

1.1.3.3 On the combined effects of UDS and climate change on FSAs.

Climate change (CC) has been a constant focus of concern for practitioners and researchers as it is one of the most significant challenges of modern civilisation (Narayan et al., 2012; Jenkins et al., 2018; Jian et al., 2021; IPCC, 2022). This is because climate change's impacts are uncertain and could involve catastrophic events and hazardous scenarios endangering life, economy, and infrastructure on a global scale. Increasing human activities, such as land use changes, have exacerbated the effect of climate change on a global and regional scale. To quantify the impact of climate change on factors such as temperature and precipitation, climate models are used to project future meteorological parameter changes (Dunning et al., 2018; Lowe et al., 2019; Oo et al., 2019; Maghsood et al., 2019; Hirabayashi et al., 2021).

Global Climate Models (GCMs) and Regional Climate Models (RCMs) are used to inform on the effects of CC on ecosystems, public health, infrastructure, food production and water-related hazards (Prudhomme et al., 2003; Rummukainen, 2010; Zhou et al., 2019; Li et al., 2021). On a global level, GCMs project that water-related hazards will continue to increase in all regions. It is projected that in the mid to long term, CC will cause intensification of heavy precipitation, consequentially increasing the intensity and magnitude of floods, tropical cyclones, droughts, and sea level rise (Fowler and Ekström, 2009; Monbaliu et al., 2014; Jenkins et al., 2018; Prakash et al., 2020; IPCC, 2022; Fowler et al., 2023). On a regional scale within the UK, future climate projections provided by UK Climate Projections 2018 (UKCP18) on a local scale (2.2 km resolution) show that the last decade has been, on average, 0.3°C and 0.8°C warmer than 1981-2010 and 1961- 1990. Annual average rainfall in the UK has been 11% and 4% wetter than in 1961-1990 and 1981-2010. Additionally, precipitation is expected to increase on average by 35% for winters from 2017-2100. In 2017 alone, rainfall for the UK was 97% of the 1981-2010 average. Overall, the projections show a higher frequency of wetter winters, increasing the frequency and intensity of floods (Met Office, 2019; Lowe et al., 2019; Kendon et al., 2020).

Alongside climate change, population growth and, hence, urbanisation also pose a threat to increased flood risk and add additional strain on drainage systems (Perry and Nawaz, 2008; Fletcher et al., 2015; Casal-Campos et al., 2018; Webber et al., 2021). Commonly associated with urbanisation is the increase in impervious ground areas. For instance, using ariel photography, Perry and Nawaz (2008) quantified a 13% increase in impervious ground from 1971 to 2004 within the UK. The population of the UK is projected to increase to 73.3 million by 2037 from an estimated population of 63.7 million in 2012 (Miller et al., 2014). An obvious implication of this projected growth in population will be an increase in housing and, thus, an increase in the urban landscape. An increase in urbanisation is also associated with a change in land use, which further impacts the hydrological regime (Butler et al., 2018; Rodriguez et al., 2021). As extreme weather events such as heavy rainfall and storms become more frequent, CC risk to cities and critical infrastructure within towns are expected to rise rapidly. The increase in rainfall extremes and hence flooding poses a significant challenge to urban infrastructure and the drainage system, which plays a critical role in managing and mitigating flood risk in urban areas (Waters et al., 2003; Semadeni-Davies, 2006; Nie et al., 2009; Marsalek et al., 2012; Arnbjerg-Nielsen et al., 2013; Lashford et al., 2019; Birkinshaw et al., 2021).

Several studies illustrate the impacts of CC on urban drainage and flood management. Marsalek et al. (2012) found that if rainfall depth increased by 15% from 25.5mm to 28.5mm, the runoff volume increased by 400 m^{3,} leading to an increase in peak discharge, and the stormwater sewer system does not convey the resulting flow which led to surcharging in Ottawa, Canada. Christensen et al. (2006) demonstrated that climate change increases surcharge in flooded areas and the number of buildings affected. The study was conducted in Odense, Denmark, and used the A2 climate change scenario (i.e., high emissions future used by the IPCC) of the return period of 10, 50 and 100 years. A large-scale study conducted by Semandeni-Davies et al. (2006) in Helsingborg, south Sweden, showed that 2.5 million m^{3} of sewage will be discharged via CSOs over the ten years from 2071 to 2080. This was approximately a 200% increase from the 0.8 million m^{3} estimate in the ten years from 1994 – 2003. Nie et al. (2009) found that the total number of flooding manholes will increase 2-4 times, with the number of surcharging sewers changing dramatically and even with small changes in rainfall. Waters et al. (2003) found that rainfall increased by 15% under climate change scenarios for the Malvern urban catchment in Canada, increased runoff by 19% and pipe surcharge by 24%.

The UFR approach has been used to assess the impact of land use change and support decision-making processes. However, there has been limited exploration of the combined effects of urban drainage systems and UFR, especially when detailed information about the drainage system is unavailable. Additionally, little attention has been given to understanding the influence of climate change on identifying flood source areas using the UFR approach. A study by Maghsood et al. (2019) investigated climate change's implications on flood source areas in the Talar Basin of northern Iran. The study combined the UFR approach with General Circulation Models (GCM) from the Couple Model Intercomparison Project Phase 5 (CMIP5). The findings revealed that climate change resulted in an increased priority ranking of several subcatchments in the area, indicating their heightened contribution to flooding and elevated sensitivity to CC. However, limited literature is available on how source areas significantly contribute to flooding within a catchment change when considering the combined effects of the drainage system and climate change. Further research is needed to understand this aspect better. Evidence for climate change and urbanisation calls for vigorous testing and implementation of adaptation strategies to both these variables (Adger and Barnett, 2009; Runhaar et al., 2012)

1.1.3.3.1 Objective 3

Due to the limited body of work available on the combined effects of drainage representation and climate change within the broader topic of flood risk modelling and the UFR approach, the 3rd objective of this thesis is to investigate the combined effects of UDS and CC on FSAs using the UFR approach. To achieve this objective, the following research questions will be addressed.

(i) How does the representation of drainage infrastructure and climate change in flood models impact the identification of FSAs and the assessment of flood risk using the UFR approach?

1.1.4 Aims, Summary of Objectives and Thesis Structure.

This thesis aims to advance the unit flood response (UFR) approach for identifying flood source areas (FSAs) in urban environments, with a focus on enhancing flood risk management. Specifically, the research seeks to refine the application of 2D hydrodynamic models within the context of the UFR approach and assess their relevance in urban catchments. Additionally, the thesis aims to create a nationally applicable method for representing drainage in flood models and evaluate its impact on flood source area identification.

To achieve the aim, the following specific objectives have been identified:

1. Conduct a comprehensive comparative analysis of how different hydrodynamic models, such as TUFLOW and HEC-RAS, identify FSAs using the UFR approach.
2. Develop a robust methodology for representing the urban drainage system (UDS) in flood models, ensuring its effectiveness and applicability.
3. Investigate the combined effects of urban drainage systems (UDS) and climate change (CC) on flood source areas using the UFR approach.

The structure of the thesis is as follows:

Chapter 2: Literature review on current standard methods for FSA identification.

Chapter 3: Application of the UFR approach through a case study in Leeds, utilizing two software packages for improved methodology applicability.

Chapter 4: Presentation and analysis of the Capacity Assessment Framework (CAF) for the city of Leeds, enhancing understanding of the dataset and its role in representing drainage systems in models.

Chapter 5: Application of a methodology derived from CAF to define drainage infrastructure in three Leeds catchments.

Chapter 6: Assessment of the catchment most sensitive to drainage representation, exploring potential changes in the spatial distribution of source areas under scenarios such as drainage system representation and climate change.

Chapter 7: Thesis synthesis, offering recommendations for further research.

This revised structure aims to provide clarity regarding the research goals and the specific objectives to be addressed throughout the thesis.

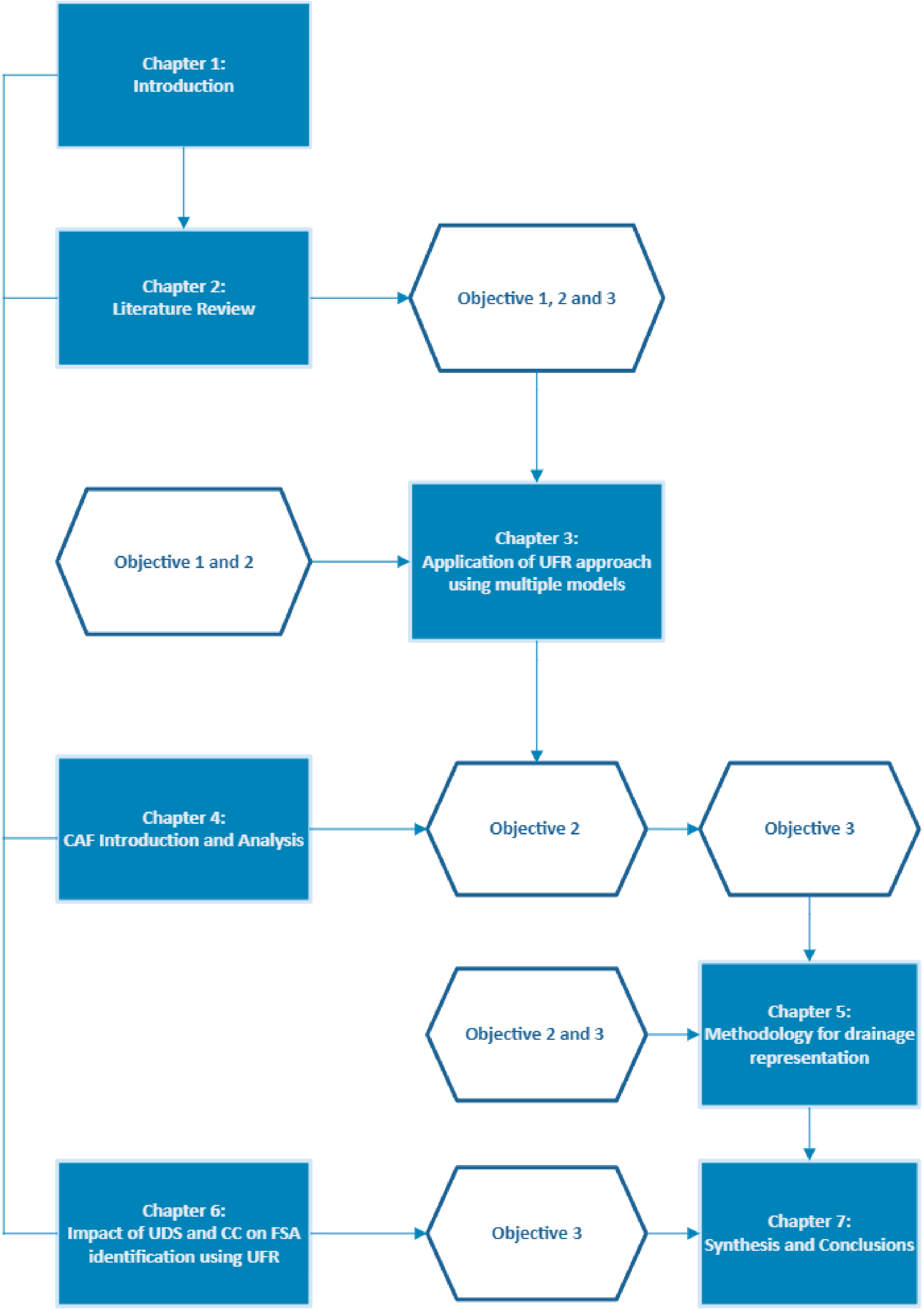

Figure 1-3: Overview of the thesis structure

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Chapter 2 A Review of Modelling Methodologies for FSA Identification

Abstract

Flooding is an important global hazard that causes an average annual loss of over 40 billion USD and affects a population of over 250 million globally. The complex process of flooding depends on spatial and temporal factors such as weather patterns, topography, and geomorphology. In urban environments where the landscape is ever-changing spatial factors such as ground cover, green spaces and drainage systems have a significant impact. Understanding source areas that have a major impact on flooding are, therefore, crucial for strategic flood risk management (FRM). Although flood source area (FSA) identification is not a new concept, its application is only recently being applied in flood modelling research. Continuous improvements in the technology and methodology related to flood models have enabled this research to move beyond traditional methods. Such that, in recent years, modelling projects have looked beyond affected areas and recognised the need to address flooding at its source, to study its influence on overall flood risk. These modelling approaches are emerging in the field of FRM and propose innovative methodologies for flood risk mitigation and design implementation, however, they are relatively under-examined. In this paper, we present a review of the modelling approaches currently used to identify FSAs i.e. Unit Flood Response (UFR) and Adaptation Driven Approaches (ADA). We highlight their potential for use in adaptive decision making and outline the key challenges for the adoption of such approaches in FRM practises.

2.1 Introduction

Flooding is characterised by the overflow of water onto dry land (Parker, 2000), while this is part of the natural water cycle, the impacts are significant and influenced by both the frequency and magnitude of flood events (Roxy et al., 2017). The combined increase in urbanisation and the effects of climate change project an increase in the frequency of extreme weather events that lead to flooding (Reynard et al., 2001; De Vleeschauwer et al., 2014a; Balsells et al., 2015; Miller and Hutchins, 2017; Haghighatafshar et al., 2018; Mignot et al., 2019; O'Donnell et al., 2019). Consequentially, this projected increase in flood risk will negatively affect economies, livelihoods, infrastructure, and health. This has underpinned the need to study the physical causes of flooding, its potential impact on society, and how to respond effectively (IPCC, 2014).

Studies in the 1940s primarily assumed that the upstream reaches of a catchment were the main contributors of stream flow and runoff to downstream areas and floodplains, referred to as Horton's theory of overland flow (Bernier, 1985; Horton, 1945). Hortonian flow identifies overland flow as the product of high rates of precipitation surpassing rates of soil infiltration (referred to as infiltration excess overland flow). Building upon Horton's theory, Variable Source Areas (VSA) emerged as a complementary concept but proposed two differences from Horton's Theory (Hewlett and Hibbert, 1966; Bernier, 1985; Hibbert and Troendle, 1988):

1. the contribution of a drainage basin varies on spatial and temporal scale
2. precipitation received by saturated soil results in runoff, hence, subsurface flow is a major contributor of runoff in a vegetated basin, also known as saturation excess overland flow

VSA characterises runoff as a dynamic process stating that catchment contributing areas (i.e. the sources of excess water) depend on the characteristics of the rainfall event and catchment itself. For example, VSA accounts for the temporal dynamics of seasonality, recognising that runoff expands in the winter and shrinks in the summer (Lim, 2016). Similarly, the size of the area that contributes to flooding is a product of the duration of rainfall, as longer precipitation events result in the greater extent of saturated areas and increase the total area that generates runoff (Qiu, 2003). The concept of VSA improved the understanding of flood processes by identifying the importance of multiple parameters that affect flooding such as land use, topography, and soil properties (i.e. soil type, depth, and compaction) (Jencso et al., 2009; Mejía and Moglen, 2010; Miles and Band, 2015). To examine such dynamic processes and variable catchment characteristics fully depends on the ability to compute hydrological flows with enough spatial detail.

Since the 1970s, computationally based hydrological and hydraulic models have been developed to provide a simplified representation of 'real world' processes that lead to flooding. Both hydrological and hydraulic models are now established as crucial tools for managing excess water. Hydrological modelling has been traditionally used to model the generation of flow from a catchment under rainfall drivers, and hydraulic models have been used to simulate the resulting flow through river channels and floodplains (Syme et al., 2004; Krysanova and Bronstert, 2009; Jajarmizadeh, 2014; Teng et al., 2017). Increasingly, these two categories of models now overlap in their capabilities and many modelling packages enable the representation of both the hydrology and hydraulics of a catchment. In this paper, we will refer to these models generically as flood models and specify the hydrological or hydraulic components as necessary.

Research and professional modelling software can model catchment areas, rivers, and floodplains in one dimension (1D), two dimensions (2D) and three dimensions (3D). The majority of flood models solve variations of the shallow water equations to simulate overland and channel flow during a flood event. Technological advancements such as increased computational power have enabled modellers to include a more detailed representation of flood processes (Teng et al., 2017; Nkwunonwo et al., 2020); representing the dynamic concepts of VSA, Hortonian flow and saturation excess by incorporating infiltration models such as Green – Ampt and Horton equations in hydraulic models (Mishra et al., 2003; Zhang et al., 2020; Gülbaz et al., 2020).

While the availability of flood models has improved the understanding of runoff processes leading to flooding, it also established a set of traditional methodologies used to answer specific questions for FRM. For example, the identification of water depths and extents at specific locations supported the development and use of hazard mapping and damage assessments (Apel et al., 2009; Koivumäki et al., 2010; Teng et al., 2017). Although hazard identification is critical from a flood protection perspective, a clearer understanding of the whole catchment contribution to flood risk will improve the scope for broader and/or alternative interventions (Saghafian and Khosroshahi, 2005a; Dawson et al., 2020).

The last decade has seen a transformative change in methods utilised for FRM (O'Donnell and Thorne, 2020). This change is driven by the recognised need for an integrated understanding of the processes involved in flood risk, and that flood prevention and protection is key to tackling the issue. Hence, approaches such as natural flood management (NFM) and sustainable urban drainage systems (SUDS) have taken a lead in addressing flooding (Vercruysse et al., n.d.; Ghofrani et al., 2017; O'Donnell et al., 2017). NFM and SUDS type solutions provide a holistic approach to flood risk and offer multiple benefits alongside flood mitigation (Fletcher et al., 2015; Zevenbergen et al., 2017; Fenner et al., 2019; Vercruysse et al., 2019; O'Donnell and Thorne, 2020). Commonly these solutions are used as 'source control' measures to reduce runoff to flood risk areas identified through impact maps, however, there is a lack of modelling guidance to implement them efficiently (Saghafian and Khosroshahi, 2005a; Petrucci et al., 2013; Saghafian et al., 2015).

Dealing with floodwater at its source and minimising flood risk in critical locations (e.g. within the built environment) is becoming an increasingly important area of FRM and hence flood modelling (De Vleeschauwer et al., 2014b; Fletcher et al., 2015; Dawson et al., 2020). As such, researchers are revisiting the concepts of VSA to help identify the sources of flooding and steer integrated FRM with more systemic approaches and methodologies. Such studies can be reoffered as Flood Source Area (FSA) identification approaches and aim to explicitly identify how best to locate the main sources of flooding across a catchment to help improve preventative management practices.

At present, there are many systematic reviews on traditional flood modelling (Jacobson, 2011; Pechlivanidis et al., 2011; Biondi et al., 2012; Ochoa-Rodríguez, 2013). State-of-the-art benchmarking reviews are also available for many flood modelling packages (Zoppou, 2001; Syme et al., 2004; Hunter et al., 2008; Néelz and Pender, 2013). Significant literature is available on flood mitigation and management strategies such as structural flood protection, sustainable urban drainage systems (SUDS), sponge cities, and blue-green infrastructure (BGI) (Van Der Weide, 2011; Kryžanowski et al., 2014; Jato-Espino et al., 2016; Ghofrani et al., 2017; Dawson et al., 2020). Approaches and methods related to FSA identification, however, are currently poorly documented and disparately published. This paper, therefore, provides a critical review of modelling methods used for FSA identification that exist in current literature. The objective of this paper is to reintroduce the concept of FSA identification as a tool for FRM and to summarise how flood models are currently used to identify FSAs. The review begins by defining FSA identification and presents a summary of the hydrological models, methods, and frameworks that have been used to investigate FSA, and presents a detailed account of literature that has developed and implemented methods of FSA (Section 2.2). Section 2.3 discusses the advantages and disadvantages of the described approaches regarding the adoption of FSA identification methods in mainstream modelling practises and identifies key research gaps. Last, the paper provides recommendations for further work to address the research gaps within this emerging topic (2.4).

2.2 Flood Source Area Identification

FSA identification refers to the approaches that identify source areas of flooding within a catchment. This is not to be mistaken with the source-pathway-receptor-consequence model that was implemented in fluvial and coastal flooding (Narayan et al., 2012). FSA identification approaches primarily utilise hydrological models of varying complexity and detail. For this review, it is important to define the term ‘flood models’ as it is one of the key tools used for FSA identification. Flood models/modelling refers to modelling packages that represent hydrological, hydraulic, and hydrodynamic processes, e.g., rainfall-runoff, stream flow and infiltration within a catchment. There are many hydrological models available to aid researchers and practitioners in modelling floods depending on the needs of the project (Néelz & Pender, 2013; Teng et al., 2017).

The availability of multiple models, however, presents significant challenges associated with their classification. A review of flood models conducted by Jajarmizadeh (2014), for example, identified that different users of the models and overlapping characteristics within the model itself create complexity with their classification. For this review, therefore, hydrological models are classified simply as lumped, semi-distributed or fully distributed (Cunderlik 2003; Jajarmizadeh 2014; Buddika and Coulibaly 2020). Lumped models are relatively simple as they represent catchment characteristics as average "lumped" values. They require few inputs, spatial variability is considered homogeneous, and rely heavily on water balance equations (Ghavidelfar and Reza, 2011; Lavenne et al., 2016). Semi-Distributed models have some spatial variability and are generally more physically representative and allow for a lumped quantification of sub-catchment responses (Mengistu and Spence, 2016). They are computationally more demanding than lumped models but less demanding than fully distributed models that require inputs for all parameters and therefore significant run times (Jajarmizadeh, 2014). Fully distributed physically models represent spatial variability at a higher level of detail, i.e., at a grid-scale and require measurable parameters as inputs. Fully distributed models have a two-dimension discretisation (e.g. flood depth and area) of overland surface features (Pina et al., 2016).

While there are other methods capable of FSA identification such as remote sensing, soil moisture analysis, and field observations (Islam and Sado, 2000; Foody et al., 2004; Chormanski et al., 2011; Mengistu and Spence, 2016) this review concentrates on studies that are reliant on flood models. This is because flood models are a crucial tool within research and industry when investigating flood processes and influencing FRM decisions globally (Mason et al., 2003; Priya, 2019; Papacharalampous et al., 2020). FSA identification methods have been categorised based on their modelling intent; first, those that directly apply a framework to identify FSAs, referred to as Unit Flood Response (UFR) driven approaches. Second, those that are used to identify area contributions for source control implementation, referred to as Adaptation Driven Approaches (ADA). **Figure 2-1** illustrates the main models used for FSA identification and the sub-classification of FSA identification methodologies. For a full summary of the approaches, tools and case studies reviewed see **Table 2-1**.

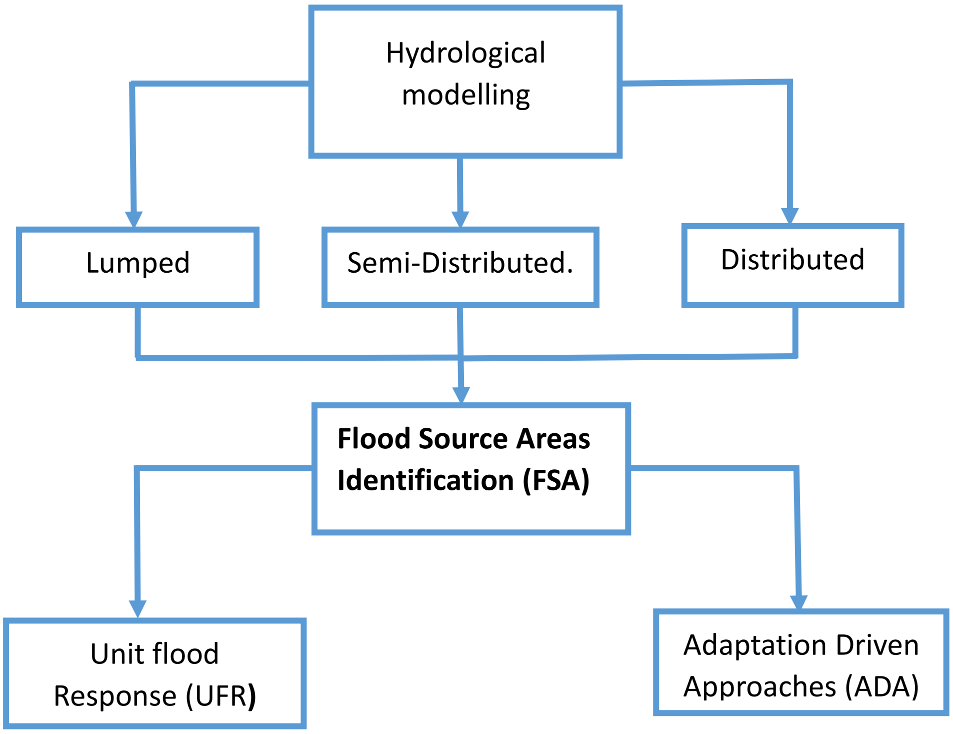

Figure 2-1: Classification of hydrological models and flood source area identification approaches

2.2.1 Unit Flood Response

The unit flood response (UFR) approach is a framework that is applied using flood models to identify source areas that contribute significantly to flood risk. This procedural framework was first introduced by Saghafian & Khosroshahi (2005). The UFR method is similar to the unit response matrix approach applied in petroleum engineering and groundwater modelling (Gorelick, 1983). Initially, the use of the response matrix was to optimise oil production and identify the drawdown curve of each well. In groundwater modelling the unit, response matrix is used to quantify the effect of sink/source rates at pre-selected well locations on various design variables (Lee and Aronofsky, 1958; Aronofsky and Williams, 1962; Gorelick, 1983). The UFR method comprises four key steps (**Figure 2-2**), which enables the ranking of sub-catchments in order of priority based on their flood index. A flood index is generated by using either equation 6 or 7.

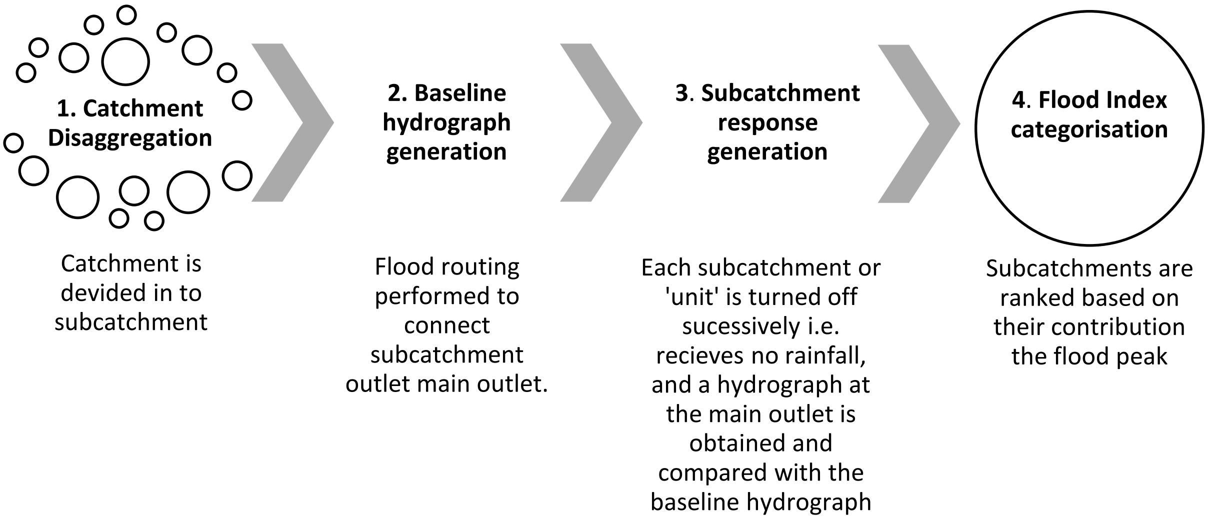

Figure 2-2: The methodological steps of the Unit Flood Response Approach

$$FI_n = \frac{Q_{bs} - Q_s}{Q_{bs}} \, x \, 100$$

Equation 6

$$fi_n = \frac{Q_{bs} - Q_i}{A_i}$$

Equation 7

Where *FI*$_n$ is the gross flood index of the sub-catchment in percentage (%); *Q*$_{bs}$ is the baseline peak discharge generated at the outlet (in m^3/s) with all the sub-catchments present in the simulation. *Q*$_s$ is the peak discharge at the outlet when *s* sub-catchment (in m^3/s) is omitted from the simulation. In equation 2, *fi*$_n$ is the flood index of the *n* sub-catchment based on the sub-catchment area (in m^3/s/km^2), *Ai* is the area (in km^2) of the sub-catchment. The UFR approach also draws heavily on the flood estimation handbook (FEH) approach to flood unit hydrographs known as disparate sub-catchments (Kjeldsen, n.d.) and the ModClark distributed model explained (see Figure 3).

Since the introduction of this approach, UFR has been used to investigate land use and spatial variability for numerous locations (**see Table 2-1**). For instance, in Iran, Bahram Saghafian et al. (2008), studied how land-use change alters the location of source areas of flood risk. Additionally, Maghsood et al. (2019) utilised the Coupled Model Intercomparison Project Phase 5 (CMIP5) General Circulation

Models (GCM) to investigate the impact of climate change on FSAs. The modelling simulations revealed that climate change projections increased flood sources located closest to the catchment outlet. Furthermore, the application of UFR by Basin et al. (2015) has demonstrated that sub-catchments that have high discharge rates are not always the key contributors to flood risk. This was due to the routing of waterways and the location of the sub-catchments, which altered their contribution to the overall flood impact. Although UFR is mostly applied to case studies in Iran, an effort has been made to understand its applicability to catchments in other countries.

Sanyal et al. (2014), for instance, uses the natural reserve conservation service curve number (NRCS-CN) approach for runoff estimation in the data-sparse Konar Reservoir in India. The study aimed to investigate the impact of land-use change on FSAs. Two land-use maps were generated using satellite images from the year 1976 and 2004. Following the generation of a baseline hydrograph for both the scenarios, the UFR approach was applied to establish the contribution of each sub-catchment. A positive correlation between land-use change at a sub-catchment scale and its impact on the flood peak at the outlet was established. However, the results also indicated that other factors such as the timing of storm event, slope, sub-catchment size and shape also have a significant impact on the results, which alter the hydrological response of a sub-catchment. The study also identifies a limitation for the UFR method to FSA identification, stating that UFR method is ideal if a singular land use condition is investigated. Land use and land cover changes, however, are dynamic in space and time resulting is complex hydrological responses. Hence, source areas identified through UFR change based on hydrological factors such as season, duration, and soil types. Abdulkareem et al. (2018) also investigated land use and its impacts on peak discharge at the catchment outlet. Flood hydrographs for the year 1984, 2002 and 2013 were simulated to observe changes in peak discharge and runoff volume for varying land use and land cover for the Keletan Basin, Malaysia. The methodology adapted the UFR approach, however, to consider the initial peak flow per unit area and the change peak flow per unit area.

The UFR framework has additionally been used to show the importance of spatial variability in rainfall when investigating FSAs. The impact of spatial rainfall on the flood index of sub-catchments was further examined through Monte Carlo analysis (Saghafian et al., 2013). The simulation and analyses concluded that the use of spatially varied rainfall has a significant impact on the prioritisation of FSAs. The results indicate that prioritised flood source areas are sensitive to the spatial distribution of more frequent rainfall events, rather than rainfall events that have high return periods. Dehghanian et al. (2019), compared the UFR approach with self-organising feature maps and fuzzy c-means (SOMFCM) algorithms as a method for applying FSA identification, however, it is difficult to make a direct comparison between the two approaches, since SOMFCM cannot provide absolute values for FSA and hence cannot be represented on a map.

Roughani et al. (2007), applied *isochrones* for spatial analysis and sub-catchment grouping. Isochrones or isochronal areas were generated by using a distributed model of time concentration developed in ArcView. *Isochrones* are used for sub-catchment grouping based on their spatial heterogeneity. The principal aim of the study was to introduce an alternative method for prioritisation of FSAs, however, after generating the *isochrones* the method utilises the UFR approach. The *isochrones* are obtained for a group of seven sub-catchments within Khanmirza in the south-east of Iran. The study found that areas that are within isochronal area 1 and 2, located closest to the outlet, have the least impact on the flood peak. Whereas, sub-catchments that are in isochronal area 5, have the greatest effect on the flood peak, even though it was the smallest in size.

Saghafian et al. (2010) introduced Iso-flood severity mapping as a fresh approach for FSA identification representation. The method introduced the unit cell approach (UCA), which superimposes a grid to disaggregate catchments, instead of irregular hydrological sub-catchments. The ModClark method explained in **Figure 2-3** was used to account for spatially distributed rainfall, losses and storage within a catchment. The underlying assumption of the ModClark model is that the velocity of the flow is uniform over the entire area and the duration of runoff to the outlet is directly proportional to the distance from the outlet (Kull and Feldman, 1999; Bhattacharya et al., 2012).

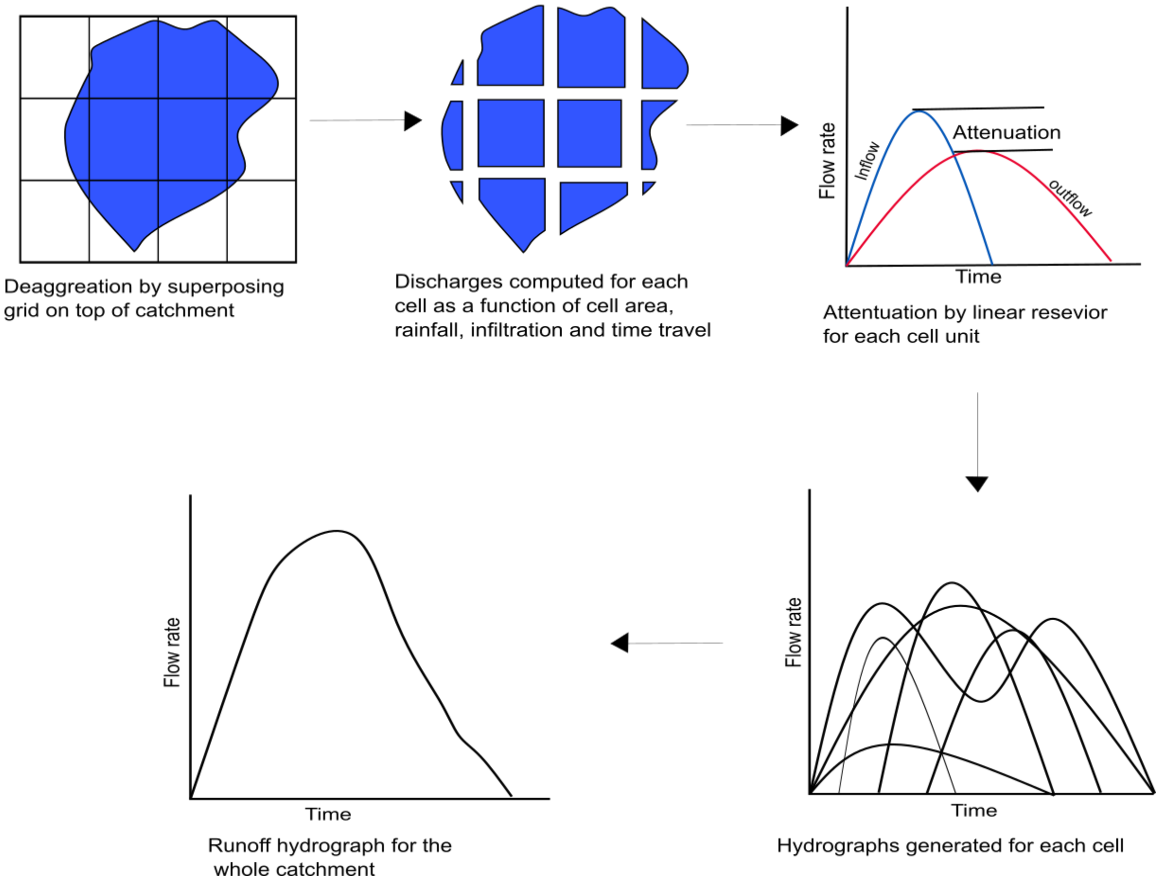

Figure 2-3: ModClark distributed model adapted from (Kull and Feldman 1999); where the study area is divided into uniform cells, runoff for each cell is determined and lagged based on the travel time to the outlet. Runoff is also directed through a reservoir

The study compared the subs-catchment approach and the unit cell approach to identify which method is best suited for FSA identification. The study area was subdivided into 278 cell units of 2km^2, where each cell unit represented a sub-catchment. Following this, the URF approach was applied to obtain a hydrograph that quantifies the effect of each cell unit at the main outlet. The results indicated that the sub-catchment approach to disaggregation and hydrograph generation would suffice if FRM was to occur at a sub-catchment scale, and the requirement for a distributed model at a fine-scale is not essential. Similar to Saghafian & Khosroshahi (2005), Saghafian et al. (2010) found that the largest, or the closest, catchments do not contribute the most or rank as high priority areas.

Rezaei et al. (2017) also utilised the ModClark model to investigate spatial variability in flood source areas. Using the URF approach the study concluded the unit cells that contained soil class D (clay-rich soils) contributed the most to overall flood risk and recommended that forest-cliff, dry land and rangeland surfaces should be prioritised for flood management within the study area.

Furthermore, FSAs increased from downstream to upstream in sub-catchments, however, this distribution pattern is not observed when compared to cell units.

The most recent advancement of the UFR approach is the utilisation of the artificial neural networks (ANN) optimised using genetic algorithms (GA) to predict contribution at a cell scale. The study conducted by Dehghanian et al. (2020), compared the flood index outputs generated by the UFR approach using HEC-HMS and ModClark with the outputs generated by ANN-GA. The study identified hydrological homogenous regions (HHRs) using SOMFCM (explained previously). Following the identification of HHRs, the ANN-GA is used to predict flood indexes in the HHRs at a cell scale. The results indicated that the spatial pattern of flood index generated by the UFR approach using the ModClark model and the ANN model were similar. The study concluded that for semi-arid catchments, ANN-GA is effective in identifying flood source areas and generating a flood index. To summarise, the UFR approach has been developed and applied using a range of innovative tools and discretizes a study area into “units” which can either be represented as a uniform grid or multiple sub-catchments. In reviewing the UFR literature, the following key conclusions have been made:

- The spatial distribution pattern of source areas (i.e., location of FSAs) differs when using the unit cell approach vs sub-catchment approach.
- There is a non-linear relationship between the input variables (e.g., rainfall, land use) and the flood index generated using the UFR approach. Therefore, the hydrological factors of the sub-catchment should be heavily considered when generating a flood index.
- Units reach a ‘steady’ state of response when subjected to higher return periods, meaning that all units contribute somewhat equally at higher return periods. However, it is unclear if the shape or size of the units impact the steady-state response.
- Spatial variability in rainfall and climate change factors influence the contribution and placement of flood source units.

Table 2-1: Summary of studies that apply Flood Source Area (FSA) identification approaches listed by modelling method. Studies highlighted in blue belong to the unit flood response (UFR) approach and those in green belong to the adaptation driven approach (ADA).

Model		**Location**	**Size (km^2)**	**No. of sub-catchments/cells**	**Contribution**	**Source**
Lumped	**HEC-HMS**	Damavand, Iran	758	7	The first introduction of the UFR approach	(Saghafian and Khosroshahi, 2005a)
		Golestan, Iran	4,802	11	Application of UFR to quantify the contribution of FSA from land-use changes.	(Saghafian et al., 2008b)
		1. Tangrah, Iran 2. Walnut Experimental watershed	1,970 93.4	6 5	Comparative study of UFR & “Self-Organising Feature Mapping Fuzzy c-means” to identify hydrologically homogenous regions.	(Dehghanian et al., 2019)
		Golestan Province, Iran	n/a	9	Demonstration of the differences in prioritising source areas based on UFR and discharge at the outlet	(Basin et al., 2015)
		Konar Reservoir, India	998	124	Impact of varying land use on flood peaks; data-scarce environment	(Sanyal et al., 2014)
		Kelentan River Basin, Malaysia	6281	4	Assessing the impact of land use/land cover on FSA includes a new index for sub-catchment ranking.	(Abdulkareem et al., 2018)

	Runoff curve number estimation	Niger	141	12	Applied a simplified hydrological method (e.g. elementary territorial units) to analyse sub-catchment contributions during a flood event: flood risk evaluation method (FREM).	(Fiorillo and Tarchiani, 2017)
Semi-distributed and Distributed	**HEC-RAS & Mod Clark**	Roodzard, Iran	900	278 ‘cell units’	UFR carried out at a pixel scale. Development of the iso-flood mapping method for FSA and output visualisation.	(Saghafian et al., 2010)
		Khanmirza catchment, Iran	391	7 sub-units, unit cells unstated	Compared distribution patterns of unit cell approach to sub-catchment approach	(Rezaei et al., 2017)
		1.Tangrah, Iran 2. Walnut Experimental watershed	1,970 93.4		Compared the use of artificial neural networks (**ANN-GA**) and ModClark for FSA identification.	(Dehghanian et al., 2020)
	SWAT	Talar River Basin, Iran	1727	21	Applied the UFR approach to quantify the contribution of source areas due to climate change.	(Maghsood et al., 2019)
	RAFTS	Pole Manjahnigh sub-catchment, Iran	284.6	7 Isochronal areas	Applied a Tc model for sub-grouping & prioritisation based on land use for FSA.	(Roughani et al., 2007)
	N/A	Hoder catchment, UK	N/A	2634 tiles	Identified and mapped the effect of changes in land use parameters to discharge at the outlet, using algorithmic differentiation and mosaic impact maps.	(Ewen et al., 2013)

	CityCAT	Newcastle-upon-Tyne, UK	9.15	37	Introduction of source-to-impact analysis as a criterion for intervention prioritisation	(Vercruysse et al., 2019)
	SWMM	Espoo, Finland	0.105	-	Introduction of FSA as a function of slope, contributing area and water depth to improve the application of SUDs	(Jato-Espino et al., 2016)
	MOUSE	Novi Sad, Belgrade	-	-	Promoted site-specific implementation of SUDs, areas that score high on the suitability value were best suited for source control measures	(Makropoulos et al., 2001)

2.2.2 Adaption Driven Approach (ADA)

Adaption driven approaches refer to approaches that go beyond just FSA identification. The fundamental difference between UFR and ADA is that the unit flood response has a defined procedural method to identify a unit as a major source of flood risk in the area, whereas ADA methodologies used to identify FSAs are variable. For instance, coupled geographical information systems (GIS) with flood modelling are used to identify areas best suited for sustainable urban drainage systems (SUDs) intervention within an urban catchment in Espoo, Finland (Jato-Espino et al., 2016). This method identifies locations that would benefit from SUDs; in order to identify as a location that would benefit from SUDs the location required to have:

1. contributing area of < 1.2 ha.
2. < 5% slope.
3. a water table depth of >0.6m.
4. low infiltration rates.

Two major aspects that were considered as identifying flood sensitive areas were flooded sewer nodes in the model, and peak flows within the sub-catchment. SUDs were implemented within these areas in the flood model, and their hydrological response was investigated. The study found that SUDS reduced discharge within the catchment by 50% (Jato-Espino et al., 2016). The results from this study highlight the importance of site-specific SUDs application for optimising SUDs performance, and, although not the main aim of the study, it provides an approach to FSA identification.

Vercruysse et al. (2019) followed the UFR method for FSA identification, however, they emphasise the interactions between flood dynamics and existing urban infrastructure systems to prioritise intervention locations (called source-to-impact). The analysis was applied to the urbanised city centre of Newcastle-upon-Tyne (~9km^2 in area) using a fully distributed hydrological model. Spatial maps were generated and used to identify locations for adaptation and FRM intervention, based on flood dynamics (e.g. depth and extent of exceedance) and land use areas (e.g. green space and existing infrastructure). The novelty of the study is the application of the UFR method to an urbanised catchment in an object driven manner. The study highlights that identifying FSAs can be beneficial to developing preventative adaption plans within the catchment, especially in an urban catchment, and how different criteria can target and change source areas. The study identified four key criteria:

1. Flood extent generated by each cell.
2. Maximum flood depth generated by each cell.

3. Land-use type flooded by each cell.
4. Flood exposure to buildings and roads cause by each cell.

For instance, if criteria three were used to guide spatial prioritisation for flood interventions, floods that commonly affect green spaces will be less critical. These criteria's can also be compared and combined to identify the most suitable intervention locations. However, it is worth noting the storm water management model (SWMM) used in Finland and CityCAT applied in Newcastle are both fully distributed models, and therefore, would not be considered a viable tool for investigations of FSA in locations where input data is scarce, resources are limited. For instance, utilising CityCAT to apply the UFR method would require significant run times and data inputs. Furthermore, the study conducted by Jato-Espino et al. (2016) makes use of sewer network data, which is in most cases is not openly or easily available.

Identifying areas best suited for SUDs implementation has also been investigated in Novi Sad, Belgrade. Although the study doesn't directly address FSAs, the method can be used for FSA identification. Makropoulos et al. (2001), utilised IDRISI, a GIS tool, to identify application areas for source control measures in Novi Sad (Serbia). Novi Sad has a mixture of peri-urban and extreme urban areas and is home to one of the oldest drainage systems within the Balkan countries. IDRISI was used with the MOUSE drainage model, which represents the artificial drainage system and the catchment as two distinct components in the model. The catchment model was divided up into a series of small sub-catchments connected to a node within the drainage network. The hydrological parameters for each sub-catchment were applied to simulate runoff. The initial output from the study was to generate a suitability map, identifying areas best suited for SUDs intervention, achieved by processing field data into IDRIS and analysing it using multi-criteria analysis module. The module utilises an order weighted area technique on multiple field data such as topsoil, type, and slope, generating an output suitability map. The suitability layer was used in combination with the sub-catchment layer to 'extract' a mean suitability value for each sub-catchment. Areas that score high on the suitability value were best suited for source control measures, therefore it could be assumed that these areas are the main FSAs. After applying source control methods, the study found a decrease in water and discharge levels, especially for rainfall events that have a short return period. For instance, for 10-year and 2-year storm events, a 7% and 12.5% reduction in volume was observed, respectively. Similar to the findings of Jato-Espino et al. (2016) and Vercruysse et al. (2019), Makropoulos et al. (2001) study highlights the importance of using FSA identification as a framework for implementing flood source control measures and driving adaptation of urban areas systematically, without neglecting critical city infrastructures such as roads, buildings and urban drainage.

ADA research efforts, so far, have been applied using complex distributed hydrological models for FSA identification, however, the availability of complex models is limited in developing countries. Fiorillo and Tarchiani (2017) developed a flood risk evaluation method (FREM) to identify areas that contribute to flood risk for a catchment located southwest of Niger. The underlying principle of the method is based on curve number runoff estimation equations, rather than distributed modelling. The motivation for this research was the optimisation of retention measures that help reduce runoff. Areas are grouped into an Elementary Territorial Unit (ETU), which is a collection of areas that have a similar slope, soil type and land cover within the catchment. The assumption is that each ETU has a homogenous hydrological response (HHR) to rainfall, also known more widely as a Hydrological Response Unit (HRU). FREM uses open-source data from remote sensing and uses GIS for analysis and, therefore, the method is computationally efficient and inexpensive. ETUs are then used to establish the current state of flood risk within the catchment, and two maps are derived using GIS. Namely, runoff maps that present areas with the highest runoff coefficients and priority maps that present sub-catchment units with high runoff coefficients (source areas). Water retention measures are implemented using runoff reduction coefficients in the sub-catchment units that rank high on the priority maps. The approach utilised within this study is one of the simplest approaches presented within this review. The approach simplifies the SWAT (soil and water assessment tool) model principles and is considerate of limited funding, skills, and technology available in developing countries that often cause challenges for the use of FRM practises. The FREM approach based on simple curve number estimation is empirically based and considers important parameters such as runoff depth and land surface conditions. The approach is unique in ADA, as it makes use of free open-source data such as Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model (DEM), and the Soil and Terrain Digital Database (SOTER). It is the only approach so far that is inclusive of the receptors/consequences of flood risk i.e. local community. For the validation of ETU, Fiorillo & Tarchiani (2017) conducted field investigations and participatory mapping with village locals. This enables GIS analysis to be merged with local perspectives, facilitating a truly integrated approach to FRM and FSA identification.

Last, ADA's can be used to concentrate primarily on land use within the catchment, and its relationship with FSA. For example, Ewen et al. (2013) investigated the causal link between land management and flood risk using reverse algorithmic differentiation. The method involved utilising mosaic tiles to signify the spatial variations in land use management and soil type. Modelling was used to generate impact mosaic maps for source and impact investigation. The model comprises 2,634 mosaic tiles, superimposed within 500m regular cells. The impact mosaic maps demonstrated the contribution each tile makes at the outlet of the catchment if land management were to change in the study area. A total of 100 parameter sets representing land use were utilised for modelling the catchment before and after land management changes. The various versions of the model are then used to identify the peak flow rate at the outlet of the catchment. This is done for each mosaic tile within the modelling domain, generating a map that shows the sources of impact.

Research grouped as ADAs have highlighted the importance of linking FSAs to adaptation and mitigation. The following key points have been summarised from the studies discussed in this section:

- Novel approaches are used for FSA identification, which allows the modeller to implement a method that is tailored to the data, technology, and resources available to them.
- Processes to identify FSAs when drainage data is available have been identified and implemented.
- Techniques for post-processing and communication of outputs generated by the UFR modelling framework have been developed and provided.
- FSA identification is a key pre-requisite for implementing source control measures.

2.3 Discussion

When reviewing research conducted for FSA identification (Table 1), the UFR approach introduced by Saghafian & Khosroshahi (2005) has been applied to several case studies, because the UFR approach presents itself as a simple procedural framework by which FSAs can be identified. This makes the application of the framework adaptable regardless of the tools used, hence, it has been applied using lumped, semi-distributed and fully distributed modelling packages. A common occurrence when investigating literature for this review was the lack of realisation that contributing source areas have been identified or a method to so do has been developed. This is because either identifying FSAs is not the aim of the study or that identification of FSAs has remained under the radar as a fundamental procedure to FRM. This review highlights the importance and benefits of identifying FSAs as a primary method for FRM, regardless of the method used. Nonetheless, it is important to note the tools use i.e. flood modes, may have a significant impact on the outcome and FSAs identified.

When reviewing the UFR methods and ADAs a clear commonality between the two approaches is the disaggregation of the catchments, i.e. dividing the catchment into smaller units to understand their wider impact. From our review, we have identified six key gaps in the current body of FSA identification research, and these represent future research direction for exploration.

1. The significance of grid/unit independence on FSA identification.
2. The effect of modelling tools on the outcome.
3. The impact of drainage systems on FSA identification.

4. Connecting source to consequence.
5. Climate change and future adaptation as per the UFR approach in practise.
6. Adopting UFR in mainstream practice.

2.3.1 Grid independence.

The unit cell approach can be criticised for being unclear on the impact of grid size on FSAs, for example, Iso-flood severity mapping or the *isochrones* approaches offer no guidance on the size of cell units that should be used for disaggregation of a sub-catchment, so far, the unit cell approach has used sizes of 2*2km^2 and 0.5*0.5km^2 (Saghafian et al., 2010; Vercruysse et al., 2019). There is no obvious logic why these dimensions were chosen to apply the UFR approach. It would be interesting to identify whether the unit cell approach follows the ideas of grid independence whereby the distribution of source areas is independent of the grid sizes. The findings of Syme et al. (2004) report that cell sizes play an important role in representing urban features and therefore may play a significant role in identifying FSAs. The issue of cell unit size has the potential to be addressed by applying the UFR to a single case study using varying cell unit sizes. The benefit of this exercise will help identify if cell unit sizes impact FSA, and how their distribution differs from when disaggregating the study area into sub-catchment.

2.3.2 Multi-model application.

Both UFR and ADA are single model applications, i.e. they have been applied to a single case study using a specific type of model. Although this has shown that FSA identification approaches can be applied using a range of models, it sheds little light on the impact the underlying code and numerical solutions have on the identification of FSAs. Questions such as does the application of models that use different numerical solutions generate identical outcomes? i.e. do all models identify the same "unit" in a catchment as the source area? Or do model performances and differences have a significant impact on the identification of source areas? Benchmarking reviews on model solutions, performance, and merits have clarified that different solutions and model codes affect the outputs generated in varying magnitudes. It is likely that FSA identification inherits the same uncertainties (Hunter et al., 2008; Neelz et al., 2010; Néelz and Pender, 2013), hence, the impact of the uncertainties due to model codes and solutions should be scrutinized and investigated to improve the robustness and credibility of methods such as UFR.

2.3.3 Artificial drainage system representation.

The lack of subsurface drainage representation is an issue not just within approaches of FSA identification, but also for the wider topic of flood modelling. However, the representation of piped drainage system becomes important when studying FSAs, as these are a critical piece of infrastructure for managing water within urban areas (Dawson et al., 2008; Möderl et al., 2009; Lim, 2016; Bertsch et al., 2017; Vercruysse et al., 2019; Dawson et al., 2020). Underground drainage systems are used to drain water away and reduce runoff within urban areas through the use of storm-water inlets (Bazin et al., 2014; Jang et al., 2018). Although drainage systems aim to augment natural drainage pathways that occur within the environment, they introduce a range of environmental and engineering challenges by modifying the hydrological response of an area (Jacobson, 2011; Miller et al., 2014; Fletcher et al., 2015). Artificial drainage systems can change the fundamental connectivity of natural overland drainage paths, thereby altering flow paths from source areas to flood impact areas. Thus, the inexplicit representation of drainage systems in the models that applied the UFR method suggests that the conclusions of the UFR modelling can be considered erroneous, especially in an urban area. For example, pluvial flooding (ponded flooding caused by rainfall intensities higher than that which can normally be drained away) has the potential to alter locations of flooding due to drainage incapacity and surcharge. Furthermore, overland flow from drainage system surcharge can increase the velocity and volume of flow increasing flooding extent and water depth (Butler et al., 2018). Subsequently, the increase in runoff volume may result in high river flow magnitude, increasing the threat of river flooding.

Generally, there is a lack of drainage data available to represent these systems in flood models, and modellers are forced to assume a generic capacity of the drainage system. For example, the rainfall reduction approach is commonly used in these cases. This is when a single depth of rainfall is used to reflect the piped system capacity and this is removed from the rainfall input before modelling overland flow (Hénonin et al., 2015; Wang et al., 2018). When assuming the drainage system operates at a set capacity, the underlying assumption is also that the system operates at full potential. In urban pluvial flooding this is problematic, as the system is often the source of the hazard itself, e.g. blockage in gullies and inlets, or surcharging manhole (Dawson et al. 2008; Ten Veldhuis 2010; Walsh et al. 2012). It is also impossible to explore intervention scenarios for the drainage system itself, as it is not explicitly represented in the models. The results from studies that apply the UFR approach in urban areas are therefore limited in their effectiveness in identifying FSA and hazards because of the unrealistic representation of key flow paths in urban infrastructure. This neglects completely, the impact of operational faults such as blockages, pumping station regimes, surcharges, and pipe capacity exceedance where pipes are designed for a smaller event. Since drainage systems change the flow paths through an area, they directly affect FSA identification and prioritisation thus, for a full understanding, the drainage system needs to be present in models.

2.3.4 Identifying connectivity of source to consequence

Similar to the challenge of representing urban infrastructure systems (i.e. the drainage network, impervious surfaces), connecting water pathways from the source to consequences is another key challenge for FSA identification. In urban areas, the connection from source areas to impact zones are catalysed by surface water processes. Surface water connectivity is regarded as a crucial element of flood processes. Therefore, it is crucial to integrate connectivity from FSAs through its flow pathways and to its receptors or impact zones. Although some ADA studies have followed the source- flow pathway- impact zone as singular elements to fully show the benefits of identifying FSA it is essential to establish the relationship of the FSA to overall flood risk. Especially, to comprehend and quantify how this disruption in connectivity affects the entire catchment (Trigg et al., 2013). Particularly in urbanised catchments, connectivity and hydraulic conveyance are of significant interest within FRM. Placement of impervious surface areas, open spaces and stormwater management structures have a significant impact on the downstream response of a catchment. While this has been addressed in the wider topic of flood risk, it has received no attention while investigating FSAs (Jencso et al., 2009; Mejía and Moglen, 2010; Ogden et al., 2011; Miles and Band, 2015; Lim, 2016). For instance, Lim (2016) identified that in urban areas the response of open space is comparable to that of impervious cover. Developed pervious areas such as urban parks closely represent hortonian flow due to components that increase hydraulic connectivity such as drainage infrastructure, roads and paths within green space. The results also highlight that identifying FSA in urban catchments is largely challenged by issues such as compaction of soil, leakages from sub-surface drainage systems and lawn watering of urban open spaces, which may increase saturation and cause saturation excess flow even during small rainfall events.

2.3.5 Climate Change and Future Adaptation.

Besides increasing urbanisation, climate change is one of the key drivers of increasing flood risk (IPCC, 2014; Watts et al., 2015; Lowe et al., 2018). For instance, in developing countries such as India the cost of flooding from 1980 to 2017 $58.7 billion as per the United Nations International disasters database. Future climate change projection for India shows an increase in extreme rainfall events which is likely to increase economic damages (Dubash et al., 2018; Ali and Mishra, 2018; Avashia and Garg, 2020). In Can Tho, Vietnam climate change-related changes such as sea-level rise and increase river flow has projected to increase flood risk within the city (Huong and Pathirana, 2013). In Jakarta mean future flood risk is projected to increase by 300% – 400% (Januriyadi et al., 2018). However, climate change and its impacts have received little attention within research focused on FSA identification. Nonetheless, studies conducted by Maghsood et al (2019) have indicated that climate change influences the distribution of FSAs.

In the UK, the effects of flooding have led to increased investment in flood defences, whereby 1,500 flood defences will benefit from £2.3 billion funding by 2021 (HM Government, 2016). However, these funding priorities protecting areas that have been recently impacted rather than identifying the sources of flooding. Applying funding to current high-risk areas may prove economically efficient today, but with climate change projections and future urban growth likely to alter hydrological and geomorphic processes i.e. the source and receptors of flooding (Stevens et al., 2016), preventative measures of source control will be more beneficial in the long-term. Using FSA identification approaches alongside climate change projections thus presents itself as a practical and strategic exercise for visualising the change in source areas and flow pathways under various climate scenarios. This would advance flood risk mitigation and management to dynamically address current and future flood risk.

2.3.6 Adoption of UFR approaches in practice.

A key question that remains unanswered is why the UFR approach or ADA has not been adopted by practitioners and decision-makers in FRM. For an approach to be adopted, ideally it would be easy to use, computational efficient/inexpensive, and incorporate enough detail for credible outputs. It is also important to consider the modelling skills required to implement the approach as a normal pre-requisite for FRM. For instance, although the UFR is a straightforward method for FSA identification, it requires multiple iterative runs (e.g. one for every cell at each time step, see (Table 1)). The resource and time challenge of running distributed and semi-distributed models is already a key limitation for hydrological modelling in FRM (Petrucci and Tassin, 2015; Teng et al., 2017). UFR inspired approaches are, therefore, likely to be viewed as computationally expensive and inefficient, depending on the detail and type of model used (Apel et al., 2009; Komolafe et al., 2015; Teng et al., 2017; Nkwunonwo et al., 2020). In developing countries, flood risk managers may not have access to a simple hydrological model for UFR or enough data for ADA. Even if a model was made available, the complexity and additional resource required may prove enough to discourage practitioners from adopting the approach over more traditional flood modelling techniques (Petrucci and Tassin, 2015).

Although conceptual models can minimise the computational power needed and establish practical UFR type approaches, the simplicity and coarse representation of catchment parameters potentially raise questions regarding the accuracy of the results and the scale of applicability for interventions. They therefore face further debate regarding the required resolution of modelling for efficient FRM (Apel et al., 2009; Jajarmizadeh, 2014). In recent years, the use of computer graphic processing unit (GPU) parallelisation offers faster simulation times (García-Feal et al., 2018; Kalyanapu et al., 2011; Prakash et al., 2020) and hence have the potential to optimise simulations that use fully distributed models, or UFR approaches. Finally, both ADA and UFR require significant post-processing to communicate the modelling outputs effectively and meaningfully, and this further raises the issue of resources and skills available for such a task to be undertaken.

2.4 Conclusions and Next Steps

This paper presents a systemic review of methods of flood source area (FSA) identification. FSA identification approaches can be categorised under unit flood response (UFR) method and adaptation driven approaches (ADA). The UFR approach identifies FSA by assessing the contribution of the sub-catchment or cell units to the flow and volume at the catchment outlet through iterative simulations. The UFR approach presents a methodological framework for FSA identification that is flexible and can be applied using varied hydrological models. However, the approach is not fully developed, as there is little or no guidance on the size of units and the impact of various parameters within those units.

ADA studies are object driven, such that FSAs are identified to implement flood risk intervention, i.e. source control measures. However, these studies are limited in number and therefore this approach requires more attention in the future. The past decade has seen advancements in methodologies designed to identify FSAs, indicating that there is a recognised need to look beyond just the affected areas of flooding. The review of the approaches in this paper represents our current knowledge of FSA identification. Despite the advancement of the approaches used to identify FSAs presented in this paper, the application of the approaches remains a challenge. To this end, the future of FSA identification is most likely a balance between cost, computation efficiency, and inclusions of missing processes. Continuous improvement in technology, however, shows the potential of reducing computational demand as a major barrier in flood risk studies. We have identified six significant avenues that remain unexplored and that have the potential to improve the current approaches of flood source area identification:

1. Investigating the impact of unit cell sizes on the identification and distribution of FSAs

2. Understanding the implications of using different flood models for identifying FSAs

3. Identifying the impact of subsurface drainage on FSA

4. Addressing the issue of connectivity and hydraulic conveyance when introducing source control measures using FSA Identification.

5. Climate change and future adaptation as per the UFR approach in practise.

6. Adopting UFR in mainstream practice.

Consideration of the above-stated points will improve our understanding of the approaches reviewed in this paper significantly, providing a greater understanding of flood processes.

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Declaration of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Chapter 3 Evaluating the Unit Flood Response Approach Using 2D Rain-On-Grid Models.

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Abstract

The unit flood response (UFR) approach assists in identifying areas within a catchment that should be prioritised for flood risk management. This spatial prioritisation method for planning and implementing flood defence and mitigation strategies has seen an increasing uptake in research. Previously, hydrological modelling and streamflow routing have been used to apply the UFR approach. We use two rain-on-grid models (TUFLOW and HEC-RAS 2D), which have become an increasingly valuable tool for flood risk management within urban areas. We apply the UFR approach for a catchment in the UK to assess the importance of model choice. The outputs from the models are used to calculate a Hazard Index (HI) to identify subunit areas within the catchment that contribute the most to flood hazard. A building exposure index (BEI) is also calculated to identify subunits that significantly increase hazard exposure to buildings. The results show that although TUFLOW and HEC-RAS 2D identify similar subunits as influential based on flooded areas, the HI and BEI are significantly different. The rankings of the HI and BEI are positively correlated to the subunit area, grey space, and green space availability. Still, catchment characteristics related to slopes have a weak negative correlation to the HI and BEI, respectively. The results from HEC-RAS 2D and TUFLOW highlight the significant computational cost associated with the methodology. The differences in the results also emphasise that the ranking of the subunits as a function of flood severity is measured.

3.1 Introduction

The unit flood response (UFR) approach to flood source area (FSA) identification introduced by (Saghafian & Khosroshahi, 2005) is a method for identifying source areas that significantly impact the overall flood risk within a catchment. The approach emerges as an alternative to traditional flood modelling methodologies, which often focus on flooded areas, i.e., impact zones. UFR provides a systematic methodology to identify FSAs that generate these impact zones and, therefore, areas optimal for source control measures. This systematic identification of FSAs is especially crucial to optimise the location and performance of blue-green infrastructure (BGI), which has become increasingly important within flood risk management (Erfan Mahmoodi et al., 2023; M. Rodriguez et al., 2021; Vercruysse et al., 2019; Webber et al., 2021; Wu et al., 2023).

Like traditional flood risk assessments, the UFR approach can be conducted using various hydrological and hydraulic models to investigate and identify FSAs (**Table 3-1**). To date, HEC-RAS, HEC-HMS and City CAT are some of the models used to identify flood source areas in Iran, India and the UK (Dehghanian et al., 2020; Maghsood et al., 2019; Saghafian et al., 2010; Saghafian & Khosroshahi, 2005; Sanyal et al., 2014; Vercruysse et al., 2019). However, these are single-model application studies; therefore, model choice's impact on the outputs for FSA identification remains unknown. This may cause discrepancies in predicting FSAs and the consequential identification of different areas as a priority for flood risk intervention. Additionally, some models may be more appropriate for UFR-type modelling regarding set-up, run times, and extracting meaningful conclusions.

Table 3-1: Models and Methods used for the UFR approach.

Model	Method	Description	Location	Source
HEC-HMS	Rainfall-Runoff Routing	Rainfall inputs are converted to streamflow to generate a flood hydrograph.	Damavand, Iran	(Saghafian & Khosroshahi, 2005a)
			Golestan, Iran	(Saghafian et al., 2008)
			Tangrah, Iran Walnut Experimental watershed	(Dehghanian et al., 2019)
			Golestan Province, Iran	(Basin et al., 2015)
			Konar Reservoir, India	(Sanyal et al., 2014b)
			Kelentan River Basin, Malaysia	(Abdulkareem et al., 2018)
SWAT			Talar River Basin, Iran	(Maghsood et al., 2019)

RAFTS			Pole Manjahnigh subcatchment, Iran	(Roughani et al., 2007)
ModClark & HEC-RAS		Flows generated from hydrologic models (ModClark) are then applied as inflows to the hydraulic model (HEC-RAS)	Roodzard, Iran	(Saghafian et al., 2010b)
CityCAT	Rain-on-Grid	Rain-on-Grid	Newcastle-upon-Tyne, UK	(Vercruysse et al., 2019)

Two-dimensional (2D) models are essential for assessing flood risk and understanding the impact of flood risk interventions. A wide range of model software and packages are available to support decision-making in flood risk management. The primary physical mechanisms that govern the flow of flood waves in 2D are mathematically described by the shallow water equations (SWEs). Modelling software can either utilise the “full” SWE e.g., ANUGA, SOBEK, TUFLOW or a simplified approximation of the SWE where some terms are omitted (Hunter et al., 2008; Neelz et al., 2010). The advantage of using simplified SWE is a more efficient use of computing power and faster run times. Besides the choice between the full and simplified equations, fundamental differences among these models include the representation of hydrological processes such as infiltration, interception, and surface retention. There are also critical differences in the discretisation schemes used by the models, where mesh can be either a regular or irregular grid (Mason et al., 2003; Syme et al., 2004; Teng et al., 2017).

Extensive literature exists on the application and performance capabilities of 2D models using the SWE and approximated equations for solving flood risk issues in rural and urban areas (Horritt & Bates, 2002; Leandro et al., 2009; S. O. Rodriguez et al., 2012; Vojinovic & Tutulic, 2009). For example, (Hunter et al., 2008) investigated the response of six 2D flood models to varying topographic parameters and found that small differences in the predicted water elevation and topography in an urban setting lead to greater differences in the predicted flooded area among the models. The Environment Agency (EA) conducted benchmark testing for fifteen models at the flood risk management and research forefront. Eight benchmark tests were used to evaluate the usability and suitability of the modelling packages for the EA flood risk management activities (Néelz & Pender, 2013). The benchmarking tests found that water levels and velocities predicted by packages such as LISFLOOD-FP were comparable to those using the full shallow water equations. It was also reported that there were large differences in the velocity prediction for inundation modelling in urban areas when using high-resolution topographic inputs; however, it is unclear if finer resolution topographic data would improve the quality of velocity predictions by the different models.

Although various 2D models are used to investigate flood risk in urban and rural areas, the applicability of these models for the UFR approach remains unexplored. The UFR approach has been chiefly applied using rainfall-runoff routing models where hydrological processes such as rainfall that cause flood flows are converted to streamflow to generate flood hydrographs. Rain-on-grid modelling is an emerging and prominent technique for simulating hydrological and hydrodynamic flood processes in 2D, particularly for storm hazard modelling (Costabile et al., 2021, 2022; David & Schmalz, 2021; Zeiger & Hubbart, 2021). While several software, including TUFLOW, HEC-RAS and Lisflood-FP, offer capabilities for rain-on-grid (RoG) modelling, the application of the UFR approach within this context is limited to CityCAT expressly, in a 9km^2 model of the city centre of Newcastle-Upon-Tyne (Vercruysse et al., 2019). Hence, there remains a lack of comparative studies assessing the different software packages for the UFR approach.

To address these gaps, this study applies the UFR approach using the RoG modelling capabilities of TUFLOW and HEC-RAS 2D (HR2D) for a large urban catchment within the UK. This enhances the applicability of the UFR approach by improving understanding of the challenges associated with the UFR approach when using modelling tools. This study also investigates the model independence of the UFR approach by determining whether the rank of importance for identified FSAs remains consistent between the two software. By assessing the capabilities and limitations of the various modelling tools, this research improves understanding of the efficacy of RoG modelling within the context of FSA. It also expands on existing knowledge about RoG modelling and urban flood management.

3.2 Methodology

3.2.1 Study Site and Data Collection

The Holbeck catchment in the southwest of Leeds in West Yorkshire, UK, covers an area of approximately 62.56 km^2 (**Figure 3-1**). The upstream of the catchment is rural, primarily comprising arable land. In contrast, the downstream reaches of the catchment are heavily urbanised, consisting of residential areas, industrial buildings, and major transport links. Green space comprises 68% of the catchment, and grey areas, such as buildings and paved and unpaved roads, makeup 28% of the area. The catchment is composed of several streams. Upper Wortley consists of Tyersal Beck, Tong Beck and Holme Beck, which feed into Pudsey Beck. Lower Wortley consists of Millshaw Beck, which feeds into Wortley Beck.

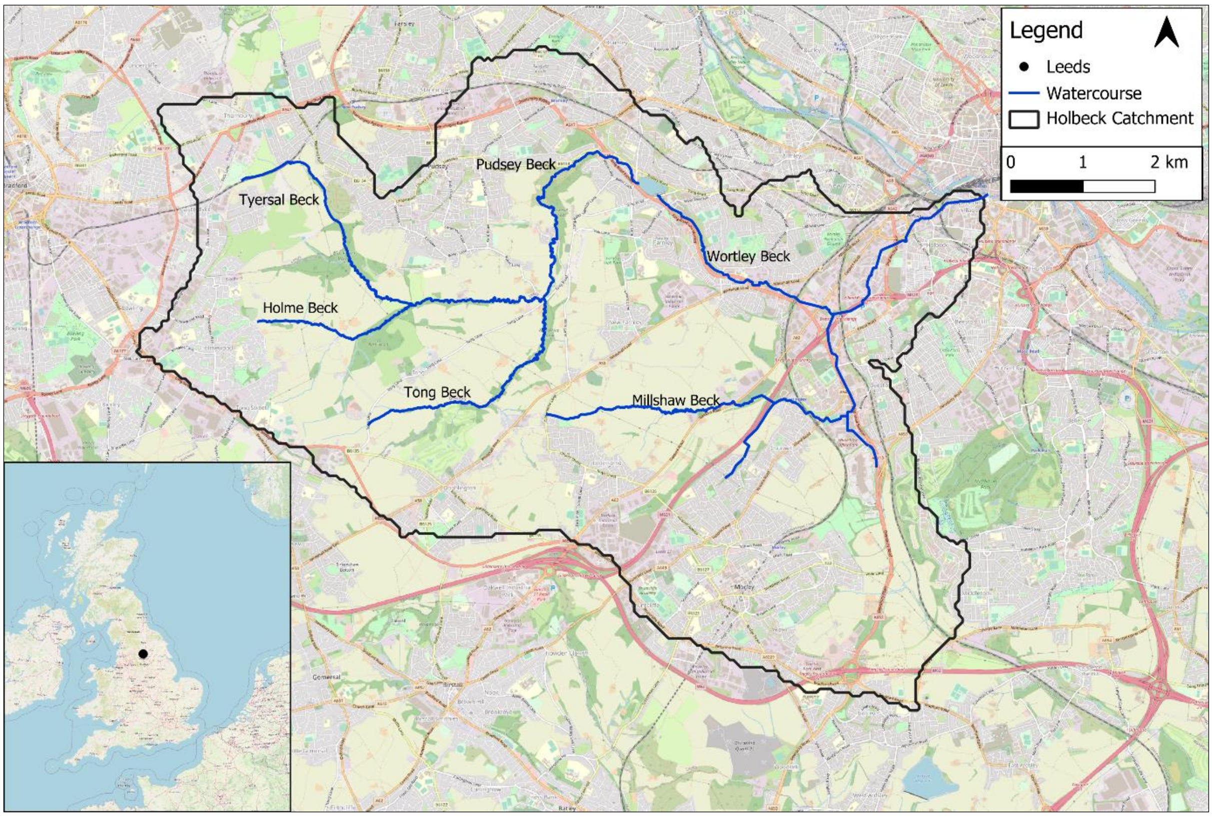


Figure 3-1: The Holbeck catchment.

On average, the catchment receives over 760mm of rainfall annually. Flooding within the catchment has been recorded since 1886 (Ahilan et al. 2014, WSP 2018). Current flood defences within the catchment include the Farnley balancing pond with an area of ~0.062 km^2 (62,000 m^2) and a storage capacity of 75,000 m^3. However, the reservoir is known to suffer from silting; hence, its current storage capacity is unknown. The balancing pond outlet comprises 16 orifices and two sluice gates on the main channel to control the outflow. The catchment also contains flood relief pipes designed to divert flow from urban surfaces to nearby storm tanks or watercourses during extreme events (WSP, 2018).

The topography of the catchment is represented using a 2-metre LiDAR. The digital elevation model (DEM) was adjusted to represent buildings and kerbs by identifying the cells overlapping with building and kerb vectors defined by the Leeds City Council (LCC) land use map. These footprints were raised in elevation by 5m, and kerbs were inserted by assuming a uniform kerb height of 0.1m. Table 3-2 specifies all the data that has been used to build the model.

Table 3-2: Datasets used in the creation of the Holbeck catchment model.

Dataset	Source	Format	Description

2 metre DEM	Environment Agency	Raster	LiDAR composite DTM at 2m resolution
Catchment Boundary	UK Centre for Ecology and Hydrology	Vector	Outlines of the boundary for the catchment obtained from the FEH web service
Land Use	Leeds City Council	Vector	Location of roads, buildings, green space, etc within the Holbeck Catchment.
Rainfall Input	REFH2	Comma Separated Values (CSV)	Design storm profiles for various return periods.
River levels	Leeds City Council	CSV (15min timestamps)	Recorded river levels at two-gauge sites

This study evaluates the impact of different rain-on-grid models on the UFR approach to identifying flood source areas. Therefore, the complexity of each model was kept as simple as possible to reduce run times. This is done by representing the main elements of floodplain modelling, such as topography and land cover, in 2D. Direct rainfall was applied to the modelling domain computed using the **Re**vitalized **F**lood **H**ydrograph (ReFH2), which uses the physical characteristics of a catchment to estimate rainfall depth for a required frequency and duration (**Appendix A, Table A-1**). The ReFH2 method was used to derive a design storm for a 1-in-100-year return period for the duration of 6.25 hours and a temporal resolution of 15 minutes. Due to the lack of explicit sewerage network data, the LCC land-use data were used to calculate a) paved areas served by storm sewer that drained toward the watercourse and b) the paved areas served by the combined sewer that drained away from the watercourse for the ReFH2. Since Holbeck is considered an urbanised catchment, the combined sewers are assumed to have a capacity of up to 12 mm/hr. Any flows runoff above this are assumed to travel overland and discharge into the watercourses (Environment Agency, 2018). The land use classification map derived friction values (n). Ten main land-use types and friction values were identified for the Holbeck catchment, shown in **Table 3-3.**

Table 3-3: Friction (n) values for the land-use types within the Holbeck catchment

Land-Use Type	**Mannings (n)**
Grass Dominated	0.04
Tree Dominated	0.06
Scrub Dominated	0.05
Unpaved Paths	0.035
Paved Paths	0.025
Building Paved Areas	0.03
Buildings	0.045
Buildings Unpaved	0.03
Waterways	0.04

3.2.2 Model Choice

The models chosen for this investigation are among the standard 2D codes previously applied to urban flood risk problems. The models are:

1. Commercially available TUFLOW HPC (2018-03-AD) with the addition of a Graphics Processing Unit (GPU) module; this module uses the processing cores of a GPU card to reduce run times. TUFLOW solves the full 2D shallow water equations, conserving both volume and momentum, and the numerical scheme is an explicit finite volume solution. The GPU solver can harness GPU cards' heavily parallelised processing capabilities, reducing run times significantly. This benefit was pronounced for a model as large as the Holbeck catchment (regarding the number of cells) (BMT-WBM, 2018). All TUFLOW model simulations utilised the Nvidia GeForce RTX 3070 GPU.
2. HEC-RAS version 6.1 is license-free and provides subgrid bathymetry as a computationally efficient approach to running simulations using high-resolution data. The subgrid capabilities of HEC-RAS allow the utilisation of a coarse computational grid without compromising the information contained in the fine-scale underlying topographic data, reducing runtimes. HEC-RAS was manually set to solve the Diffusive-Wave equation (DWE). The numerical scheme is an Implicit finite volume solution. HEC-RAS also offers the option to use the full SWE equations. All HEC-RAS simulations were run Intel(R) Xeon(R) CPU E5-1630 v4 @ 3.70GHz (3.4GHz minimum required for a model the size of Holbeck) with four core(s), 8 Logical Processor(s).

The rationale behind choosing TUFLOW is that it is one of the UK's most used industry-standard software. It is considered an appropriate tool for fluvial, urban and coastal flood modelling and facilitates flood risk management decisions (BMT-WBM, 2018; Néelz & Pender, 2013). HR2D (HR2D) introduced its module for 2D simulations in Version 5 and since has been widely used for flood mapping, making it one of the most used hydrodynamic models (Costabile et al., 2021).

3.2.3 Modelling Method

The procedure for the UFR approach can be summarised in 4 steps:

1. **Baseline Assessment** – Here, the catchment response for a 1 in 100-year return period event is generated to establish the flood risk within the catchment. For this study, this step will be conducted for each model.
2. **Catchment disaggregation** –the catchment area is divided into 'units'. These can be in the form of sub-catchments or cells of varying sizes. For this paper, we define a unit as a sub catchment of the larger Holbeck catchment. Holbeck is subdivided into 12 naturally draining subunits (Figure 2), A to K.
3. **UFR analysis** - rainfall is omitted from each unit successively, and the model is run iteratively.
4. **Flood Index Categorisation:** Each unit is ranked based on its contribution to flood risk within the catchment. Previously, studies have quantified the discharge of each unit (m^3/s) to the main outlet to establish its contribution, and this can be expressed as a per cent of total peak flow or as a function of the area.

In this paper, step four has been modified to assess risk using a **Hazard Index and Building Exposure Index (BEI) categorisation;** hence, the methods described in steps five and four have been used in its place. All flood map outputs were processed using the Australian Rainfall-Runoff (ARR) hazard vulnerability categories, which include depth and velocity thresholds for people, vehicles and structures.

Table 3-4: Australian Rainfall-Runoff (ARR) hazard categories

Hazard Category	Description
H1	Generally safe for vehicles, people, and buildings.
H2	Unsafe for small vehicles
H3	Unsafe for vehicles, children and the elderly.
H4	Unsafe for vehicles and people.
H5	Unsafe for vehicles and people. All buildings are vulnerable to structural damage. Some less robust buildings are subject to failure.

H6	Unsafe for vehicles and people. All building types are considered vulnerable to failure.

5. **Hazard Index** ranks each unit based on its contribution to the overall hazard within the catchment. Hazard exposure simulated for each scenario was assessed by applying the H2 to H6 hazard vulnerability category classification limits established by the Australian Rainfall-Runoff (ARR) categories to all depth and velocity output maps generated. Category H1 was omitted in the calculation of the hazard index because it is considered generally safe for vehicles, people, and buildings. To establish the hazard, index the original equation from the flood index developed by Saghafian & Khosroshahi (2005) was adapted; this is presented in Equation 8.

$$HI = \frac{(HI_{(all)-} HI_{(k)})}{HI_{(all)}} * 100$$

Equation 8

where, HI is the gross flood index of the k_{th} subunit expressed as a percent; $HI_{(all)}$ is the maximum flood extent (km^2) when all subunits receive rainfall i.e., baseline; $HI_{(all-k)}$ is the maximum flooded extent (km^2) with k_{th} subunit removed i.e., the UFR scenarios.

6. **Building Exposure Index (BEI)** was used to investigate the influence of the subunit on hazard to buildings using Equation 9.

$$BEI = \frac{(BE_{(all)-} BE_{(k)})}{BE_{(all)}} * 100$$

Equation 9

Where, BEI is the gross Building Exposure Index expressed as a per cent; $BE_{(all)}$ is the total number of flooded buildings when all subunits receive rainfall, $BE_{(k)}$ is the number of buildings flooded when the kth catchment is receiving no rainfall. Exposure of buildings to flood risk was assessed by applying the H5 to H6 hazard vulnerability category classification limits established by the AAR categories to all depth and velocity outputs generated by each simulation presented in Table 3. The BEI only includes H5 and H6 category as these include structural damages to buildings. Post establishing a rank for each subunit based on the HI and BEI for the outputs from both TUFLOW and HR2D, the ranks were then assessed for correlation with critical characteristics of each unit listed in **Table 3-5**.

Table 3-5: Catchment characteristics used for correlation.

Catchment Characteristics	**Description**

Grey Space	the total impervious area within each subunit
Green Space	the total area of green space within each subunit; this includes gardens, verges, swales and arable land.
Area of each subunit	The extent of a subunit
Number of buildings per subunit	Total number of buildings per subunit, includes residential and commercial buildings
Slope	as a percent of each subunit
DPLBAR	Drainage Path Length
DPSBAR	Mean Drainage Path Slope

The Spearman's rank correlation coefficient was calculated for the values of the characteristics in Table 5 and the ranking of the subunits from the HI and BEI to measure both the strength and direction of the relationship between the ranks of data. These characteristics were chosen because they are key characteristics that play a role in dictating flow paths and hazards within the catchments. A value of 1 indicates a strong relationship between two data sets. Hence, 1 is a perfect positive correlation, -1 is a perfect negative correlation and indicates 0 is no correlation. Since several of the ranks for the parameters were tied, the Equation 10 of the Spearman's correlation coefficient was used:

$$\mathrm{r_s} = \frac{\Sigma_{\mathrm{i}}(\mathrm{a_i} - \overline{a})(\mathrm{b_i} - \overline{b})}{\sqrt{\Sigma_{\mathrm{i}}(\mathrm{a_i} - \overline{a})^2 (b_i - \overline{b})^2}}$$

Equation 10

Where r_s is the coefficient, *i* is the paired score, *a* and *b* are the rank of each subunit using the UFR method in TUFLOW and HR2D, and *b* is the ranks of the characteristics presented in **Table 3-5.**

3.3 Results

3.3.1. Baseline

The baseline results presented in **Table 3-6** show that when simulating a 1-in-100-year return period rainfall event for the Holbeck catchment, HR2D estimates that 1.58 km^2 of the catchment is exposed to flooding of greater than Hazard Category H2. TUFLOW predicts a slightly higher H2 flood extent of 1.45 km^2. HR2D estimates that 384 buildings, i.e., residential and commercial properties will be exposed to flood risk. This is 3.45 % of the total number of buildings within the Holbeck catchment. TUFLOW estimates that 919 or 3.40 % of the buildings within the catchment will be exposed to flood risk.

Table 3-6: Hazard extent and number of buildings exposed to hazard in the baseline scenario for HR2D and TUFLOW, values in italics have not been used to calculate the total.

	TUFLOW		**HR2D**	
Category	Area (km^2)	No. of Buildings	Area(km^2)	No. of Buildings
2	0.55	*4376*	0.58	*1792*
3	0.43	*1171*	0.64	*1738*
4	0.19	*1015*	0.21	*998*
5	0.20	892	0.13	379
6	0.06	27	0.005	5
Total	**1.45**	**919**	**1.58**	**384**

3.3.2 Prioritisation Index Ranks

Based on the outputs, i.e., total area exposed to hazard category two and above and number of buildings exposed to hazard, each subunit was assigned a rank presented in **Table 3-7**. The HI ranks obtained using TUFLOW (**Figure 3-2**) show that subunits A, B and K are the largest contributors to flood hazard within the catchment, with an HI of 53.17 %, 44.15 %, and 43.63 %, respectively. Only two of the 11 subunits (C and D) have identical HI rankings. The HI rankings obtained by applying the UFR approach using HR2D (**Figure 3-2**) rank subunits K, A and F as the three highest contributors to flood hazard within the catchment. The HI for each subunit is 18.04 %, 17.89%, and 10.95 %, respectively. Although both software ranks the subunits similarly, the calculated index differs. For instance, the HI of subunit K has a difference of 32.68%. Similarly, subunit A shows a difference of 35.28% in the HI between TUFLOW and HR2D.

When applying the UFR approach using TUFLOW, the effect of omitting rainfall from subunits generates a more significant difference in the flooded extent than with HR2D. For instance, applying the UFR approach to Subunit A in TUFLOW results in 0.68 km^2 of the catchment exposed to hazard, applying the UFR approach using HR2D for the same subunit results in 1.30 km^2 of the catchment exposed to flood hazard above hazard category H2.

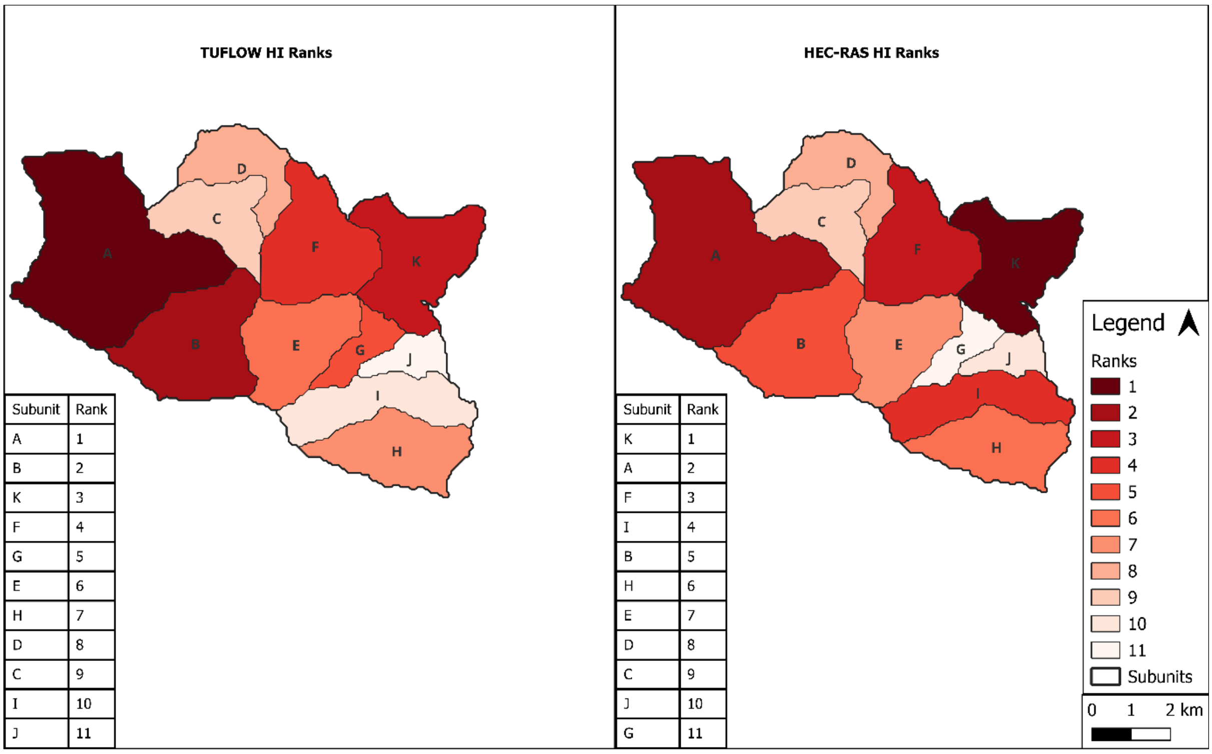
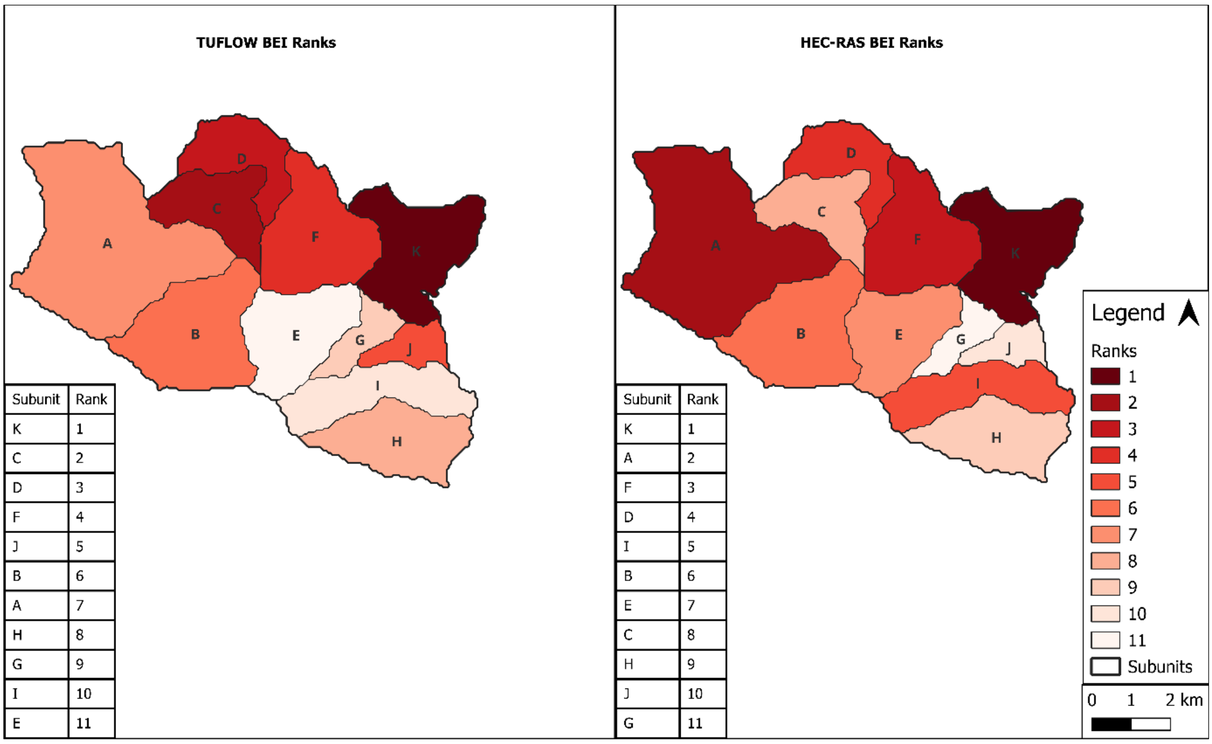


Figure 3-2: Subunit ranking of the HI ranking for the Holbeck catchment using TUFLOW (left) and HR2D (right)

The BEI rankings (**Figure 3-3**) obtained from TUFLOW identify subunits K, C and D to rank the highest where the BEI is 37.54 %, 34.82 % and 32.10 % for subunits K, C and D, respectively. Subunits K (28.90 %), A (14.84 %) and F (10.93 %) obtained using HR2D show that these subunits are the highest contributors when investigating building exposure to flood hazard. Similar to the HI, TUFLOW estimates a higher number of buildings will be exposed to hazards under each UFR scenario when compared to HR2D. For instance, HR2D indicates that 342 buildings are likely to be exposed to flood hazards when the UFR approach is applied to Subunit F. In contrast, TUFLOW identifies 627 buildings will be exposed to flood hazards of H5 and above. The largest difference in the BEI is observed for subunit B, where there is a difference of 30.65% between TUFLOW and HR2D. The slightest difference of 8.63% in the BEI is observed for subunit K, with ranks identically in both TUFLOW and HR2D.



Subunit	Rank
K	1
C	2
D	3
F	4
J	5
B	6
A	7
H	8
G	9
I	10
E	11

Subunit	Rank
K	1
A	2
F	3
D	4
I	5
B	6
E	7
C	8
H	9
J	10
G	11

Figure 3-3: Subunit ranking of the BEI for the Holbeck catchment using TUFLOW (left) and HR2D (Right)

The change in ranks for the HI and BEI between the two software is presented in **Figure 3-4**. Subunits C and D have no change in HI ranks; subunit G shows the most significant increase in rank by six. Subunits I, J and K show no rank change when the BEI from TUFLOW and HR2D are compared. The most significant change in rank is observed for subunit C where, the BEI ranks 2nd for TUFLOW and 8th for HR2D.

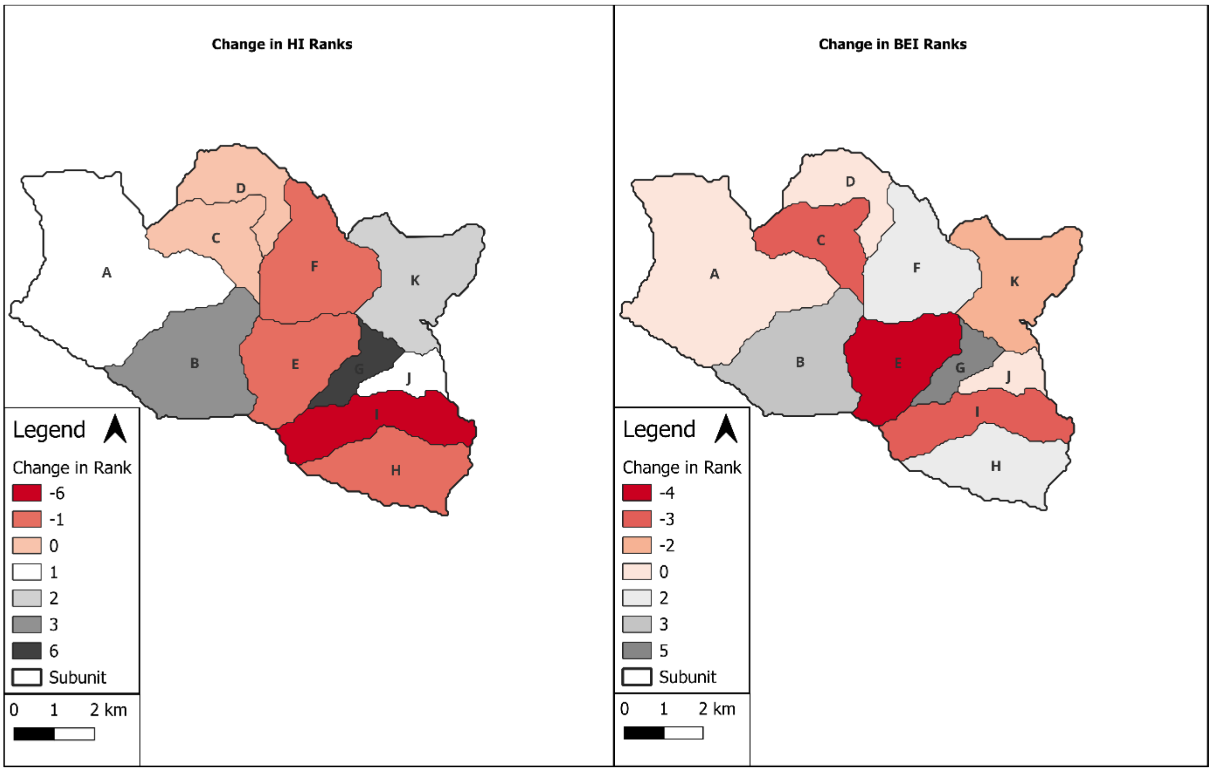


Figure 3-4: Change in ranking of the subunits for HI (left) and BEI (right) between TUFLOW and HR2D; negative values indicate that ranking decreases in HR2D, positive values indicate an increase in ranking.

Table 3-7: HI, BEI and the associated ranks for outputs from HR2D and TUFLOW

Subunit	**Hazard Index (HI) (%)**					**Building Exposure Index (BEI) (%)**				
	HR2D	Rank	TUFLOW	Rank	**Change in rank**	HR2D	Rank	TUFLOW	Rank	**Change in Rank**
A	17.9	2	53.17	1	**1**	14.84	2	30.14	7	**0**
B	7.54	5	44.16	2	**3**	7.03	6	31.01	5	**-3**
C	3.79	9	39.82	9	**0**	4.17	8	34.82	2	**3**
D	6.17	8	39.94	8	**0**	10.68	4	32.10	3	**0**
E	6.26	7	42.18	6	**1**	6.25	7	20.35	11	**-4**
F	10.95	3	43.45	4	**-1**	10.94	3	31.77	4	**2**
G	2.45	11	42.23	5	**6**	2.34	11	28.18	9	**5**
H	6.72	6	41.35	7	**-1**	3.91	9	29.92	8	**2**
I	8.15	4	39.39	10	**-6**	7.81	5	31.01	5	**-3**
J	3.49	10	39.04	11	**1**	3.39	10	26.33	10	**0**
K	18.05	1	43.64	3	**2**	28.91	1	37.54	1	**-2**

Both the FI and BEI rankings from TUFLOW and HR2D were assessed for correlation using Spearman’s Rank Correlation Coefficient (ρ) for several physical characteristics present as inputs during the model build (**Table 3-8**). The ρ ranking across the FI and BEI for HR2D and TUFLOW indicates that all attributes positively correlate to priority rankings. Grey space has a strong positive monotonic correlation to the ranks overall and is the strongest. The slope and DPSBAR demonstrate the weakest positive correlation for the final ranks.

The Spearman's Rank Correlation Coefficient (ρ) for the HI using HR2D and TUFLOW indicates the slope to have a weak negative correlation to the HI. The ρ values are -0.24 and 0.28 for TUFLOW and HR2D, respectively. The area of grey space per subunit has a very strong positive correlation (ρ 0.84) to the HI ranks obtained from HR2D and a moderate positive correlation coefficient ρ 0.47) for the HI ranks obtained by applying the UFR approach to TUFLOW. The number of buildings per subunit also shows a strong and moderate positive correlation for TUFLOW (ρ 0.63) and HRD2D (ρ 0.52), respectively. The area of the subunit also has a very strong positive correlation for both TUFLOW (ρ 0.82) and HR2D (ρ 0.84).

The ρ for the BEI ranks obtained by applying the UFR approach using HEC-RAS and TUFLOW shows that the DPSBAR has the weakest correlation to the BEI ranking. The BEI ranks obtained from HR2D indicate a very strong positive correlation for the area of grey space per subunit (ρ 0.83). However, TUFLOW shows a moderate positive correlation (ρ 0.47). For all catchment characterises except slope, TUFLOW shows a weaker correlation when compared to HR2D for the BEI. The number of buildings per subunit shows a weak positive correlation for the BEI from TUFLOW and a moderate positive correlation for HR2D. The correlation coefficient for green space for the BEI ranks for both HR2D shows a moderate positive correlation (ρ 0.50); however, TUFLOW shows a very weak positive correlation (ρ 0.10).

Table 3-8: The correlation coefficient for key catchment characteristics for the Holbeck catchment and the FI and BEI from TUFLOW and HR2D

	Spearman's Rank Correlation Coefficient (ρ)			
Catchment Characteristics	**HI**		**BEI**	
	TUFLOW	HR2D	TUFLOW	HR2D
Grey space (km^2)	0.47	0.84	0.47	0.83
Green Space (km^2)	0.59	0.63	0.10	0.50
Area (km^2)	0.82	0.84	0.22	0.68
No of Buildings	0.63	0.52	0.37	0.62
Slope (%)	-0.24	-0.28	0.41	-0.05
DPLBAR	0.67	0.67	0.17	0.67

3.4 Discussion

The collective results indicate that HR2D and TUFLOW identify similar subunits to have the most significant impact on hazards within the Holbeck catchment for a 1-in-100-year return period. Overall, only 18% of the sub-units rank identically for the HI ranking when comparing the two software. Additionally, the results show that for each subunit, TUFLOW predicts a higher HI value when compared to HR2D. The HI ranking between the two models shows a significant difference; for instance, HI ranks for subunit A in TUFLOW is 53.17 %, and HR2D is 17.9%. To investigate this further, the RoG modelling for the Holbeck catchment was conducted using the SWE and the DWE in HR2D, which found that using the SWE equation results in a higher number of buildings flooded within the catchment (**Table A-2**). In all cases, the results show that TUFLOW has a more significant impact than HR2D, even though there is a slight observable difference in the baseline results. For instance, HR2D predicts 1.58 km^2 hazard extent, and TUFLOW predicts 1.45 km^{2,} i.e., an 8.5 % difference in hazard extent. The results also show that upstream subunits are essential to hazard exposure within the catchment.

The subunits were also ranked based on their exposure to buildings within the catchment, thus advancing the UFR methodology to explore its potential use in urban settings. This improves on the original method applied to rural areas in Iran (Saghafian & Khosroshahi, 2005). The results show that the ranking of the subunits for the BEI was different between TUFLOW and HR2D. Subunit K ranks the highest for both models even though it does not have the highest number of buildings within the catchment. This is potentially because although subunit K does not have the most significant number of buildings, it has the highest area of impervious cover. In both cases, when looking at unit response assessed using flood extent and building exposure, the UFR approach appears to be a useful screening tool to identify areas that will benefit from mitigation strategies.

As indicated by the results, if the objective is to reduce flood hazard, subunits K, A, and F should be prioritised if the decision for flood risk management is based on outputs from HR2D; this changes to subunits A, K and B using TUFLOW. However, suppose the objective of implementing flood mitigation strategies is to reduce the risk of flooding to buildings. In that case, subunits K, C and D should be prioritised based on the outputs from TUFLOW, and subunits K, A and F should be prioritised based on outputs from HR2D. The results show that subunits, where flood management activities should be prioritised, depend on the model used and how flood severity is measured.

Investigating the influence of catchment characteristics between TUFLOW and HR2D found that grey space and the area of roads within each subunit strongly correlated to the HI rankings obtained for the HR2D simulations. Whereas the HI rankings for TUFLOW indicate a moderate correlation to the HI rankings. Furthermore, for both software, the slope and DPSBAR negatively correlate to the HI rankings. This suggests that although slope and slope steepness are important catchment characteristic for flooding generation, it is less influential when establishing the HI using the UFR approach (Gao et al., 2018)

The differences in the rankings between TUFLOW and HR2D add to the challenges associated with decision-making within flood risk management. The difference between the HI BEI when the UFR approach is applied using TUFLOW and HR2D presents uncertainty in informing decision makers on where and how mitigation is required within a subunit. Furthermore, the UFR approach brings issues associated with run times as multiple runs are required for each approach; this is a significant limitation of the approach. The time taken to run the model for 11 scenarios, i.e., 11 subunits for the catchment of Holbeck using TUFLOW (GPU), was 4.6 hours per run. Using the GPU module in TUFLOW reduced run times from 47.7 hours per scenario when using TUFLOW classic. On average, each model run in HR2D took 27.6 hours of run time per subunit scenario.

A vital limitation of the UFR approach, when applied to both 2D and stream flow routing models, is that it assumes that part of the catchment receives no rainfall while the rest receives uniform rainfall. This method of rainfall representation is an oversimplification of highly complex drivers for hydrological processes. Spatial variability is known to influence the timing of a runoff hydrograph. Hence, any estimation of hydrological response in this study consists of inherent uncertainty associated with spatially varied rainfall. To reduce this uncertainty, the UFR approach needs to consider the effect of the spatial variability on identifying flood source areas. For instance, using radar rainfall instead of uniform hyetographs can provide a more realistic representation of rainfall within the catchment and improve confidence in results (Cristiano et al., 2017; Singh, 1997).

3.5 Conclusion

This study applied the UFR approach to the Holbeck catchment using 2D rain-on-grid modelling in TUFLOW and HR2D to investigate if using different modelling software impacts the predicted FSAs. The methodology can be implemented within the two software with relative ease; however, it is not computationally efficient as it requires iterating through multiple scenarios.

One key outcome of this research is presenting a first multi-model comparison of the approach for the same catchment. It can be concluded that depending on the tool used, the ranking of the subunits changes. The postprocessing methodology used within this paper extends the UFR "measure" from just flood area to a hazard category and exposure assessment. This provides a different way of ranking subunits based on what is to be prioritised and may be a better measure for flood risk management strategies.

Instrumental in improving the robustness and application of the UFR approach is investigating what decision-makers require from the UFR approach and how it can be utilised in FRM practice. This should be used to refine the methodology as flood predictions simulated by models are critical to decision-makers for planning and flood risk. From a methodological perspective, further work should investigate the impact of drainage systems and spatially varied rainfall representation to improve the accuracy of the results. The challenge of validating the identified source areas should also be addressed.

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Chapter 4 Review and Analysis of Urban Drainage Capacity using the Capacity Assessment Framework (CAF)

Abstract

Drainage systems are an integral part of city infrastructure. Their main role is to transport domestic waste and stormwater to wastewater treatment plants. The design characteristics of pipes, inlets and other hydraulic structures vary based on population, weather patterns, age of infrastructure and topography. Assets classed as drainage system in the UK are owned by private companies, hence there is limited knowledge of the capacity and performance of these systems. Due to its so far limited exposure in flood research, this paper presents the capacity assessment framework (CAF) developed by Water UK in collaboration with the EA and sewerage undertakers for UK Drainage Water Management Plans (DWMP). Furthermore, it presents initial review and analysis of the CAF outputs in the context of Leeds City, UK. The outputs of the framework are aggregate risk score on a hexagon grid indicating the locations in which the performance and capacity of the drainage system is sub-optimal under current and future scenarios.

A total of 4905 km length of sewer pipes was modelled to estimate the length of pipes that will surcharge in a 1 in 30-year rainfall event (i.e., red length). It was found that by 2030, 2050 and 2080 the length of pipes that surcharge is 1036km, 1172km and 1382km, respectively. Local spatial autocorrelation is used to explore clusters and outliers associated with the risk scores to understand the performance and capacity of the drainage system in Leeds under current and future drivers.

4.1 Introduction

Drainage systems are a key infrastructure to convey, collect and store water. Before urbanisation, key elements of drainage systems were soil, gullies, porosity and permeability of rocks, stream channels, and subsurface hydrology (Booth, 1991; Butler et al., 2018). Increase in population and growth in economy, industrialisation and hence urbanisation led to the replacement of natural processes of drainage, such as infiltration, with constructions such as pipes, culverts, and forms of sustainable urban drainage systems (Bisht et al., 2016; Butler et al., 2018). Over time, drainage systems evolved from a simple ditch or gully on the side of a path to a complex network of underground pipe systems. These pipe systems are often designed to treat either foul water, i.e., waste produced at homes, stormwater, i.e., excess water because of extreme rain or a combination of both, through combined systems called combined sewer overflows (CSOs) (Smedema et al., 2004; Butler et al., 2018).

In urban areas, the main purpose of the stormwater drainage network is to direct floodwaters from built areas to a nearby watercourse, or storm tanks in treatment plants. During a storm event, a layer of run-off forms from intense rainfall and flows along streets and alleys (urban surface pathways). Eventually, this layer of runoff flows to a gully where it meets the underground pipe system. Once the drainage system has reached its capacity, it can no longer accommodate further incoming runoff, leading to a condition known as a surcharge, resulting in ponding and pluvial flooding (Mark et al., 2004; Djordjević et al., 2005; Houston et al., 2011; Ochoa-Rodríguez, 2013; Guerreiro et al., 2017; Dawson et al., 2020).

Pipes that make up a drainage system vary in material, size, length, diameter, and consequentially capacity. The stormwater drainage capacity for urban areas in the UK is usually designed to accept flows of either a 1-in-10 or 1-in-30-year return period (Zoppou, 2001; Ochoa-Rodríguez, 2013; Butler et al., 2018; Environment Agency, 2018). Therefore, a storm event of a greater magnitude than the system design capacity will often result in surcharge and excess runoff. However, in many cases, the capacity of a system is reduced due to operational malfunctions such as blockages and surcharging pipes (Schmitt et al., 2004; Palla et al., 2018).

Although the uncertainties associated with drainage system capacity due to extraneous variables such as blockages, extreme events, seasonality, and ageing are known, the capacity of these systems is still overrepresented in models used for flood risk management. Flood models are used to assess the rainfall response of a catchment and are used to answer questions about where and when it will flood. Additionally, these models are key tools in the planning and implementation of flood mitigating interventions (Teng et al., 2017; Rehman et al., 2019). The inputs into the models vary based on the catchment characteristics. In most cases, inputs such as elevation, land use and rainfall are utilised. However, the capacity of the drainage system is often assumed and misrepresented (Chang et al., 2015; Yu et al., 2016; Palla et al., 2018; Singh et al., 2021b).

One method of drainage capacity representation in flood modelling is rainfall reduction, where a constant rate of rainfall is subtracted, assuming this is handled by the drainage system (Chang et al., 2015; Wang et al., 2018). In the UK, a well-known example of the rainfall reduction approach is the first national flood map for England and Wales developed by the Environment Agency, which disregarded the function of the sewer network and set the capacity of the system to deal with 1 in 30-year storm event (Chang et al., 2015). Additionally, Wang et al (2018) also implemented the rainfall reduction approach, by applying a fixed reduction of 12 mm/hr to the design rainfall to represent the function of the stormwater systems. Chen et al (2009) applied a constant infiltration rate to represent the function of drainage systems in southeast London. Furthermore, Vercruysse et al (2019) also applied a drainage capacity estimate when modelling a 1-in-50-year flood event for Newcastle-upon-Tyne. The modelling exercise produced flood risk maps that identified source areas that contributed significantly to flood hazards in an urban domain. Assuming and estimating the capacity of drainage systems in pluvial flood modelling consequentially leads to the neglection of the source of the hazard itself. These are blockage in gullies and inlets, or surcharging manholes (Maksimović, 2009; Walsh et al., 2012; ten Veldhuis et al., 2015).

Other methods of estimating drainage capacity include the use of surcharge hydrographs at manholes, however here the assumption is that flow is unilateral and can only move from the sewer system to the ground (Hsu et al., 2000). More technical approaches such as combining sewer flow models with overland flow models (flow of water over a floodplain in two dimensions) have also been used, however, these models are computationally demanding, and require at least some information regarding the network. Lastly, generating synthetic drains has also been utilised, however, this faces significant challenges associated with validating large scale synthetic drainage models (Möderl et al., 2009; Bertsch et al., 2017). One of the key elements driving the representation of drainage networks in flood models is data availability (Fenner, 2000; Freni et al., 2009; Yu et al., 2016; Vercruysse et al., 2019).

Water UK is the trade association representing major water companies in the UK, developed the drainage wastewater management plan framework (DWMP) (Water UK, 2019; Jenkins, 2020). The DWMP enables water companies to work together and improve the robustness of drainage infrastructure for its customers and the environment. The DWMP also addresses requirements outlined in the UK government's Strategic Policy Statement to Ofwat and the Ofwat’s final PR19 methodology. The requirements outlined in these documents are focused on improving transparency and the approach to drainage and wastewater planning for long term resilience (Defra, 2017; Ofwat, 2017). The DWMP have created a set of tools to provide customers and stakeholders with more information on their drainage system. Three key tools have been developed to improve transparency and long-term planning. These tools are the capacity assessment framework (CAF), the stormwater overflow assessment framework and the wastewater resilience metrics. This paper reviews and analyses the first tool i.e., CAF which provides a consistent approach to evaluating the amount of capacity available in foul and combined sewer networks now and in the future (Water UK, 2019).

CAF provides a new opportunity to improve our knowledge on catchment drainage systems and enhance the representation of drainage capacity in models and adaptation planning (Gorton et al., 2017b; Gorton et al., 2017a; Udale-clarke, 2018; Water UK, 2019). To generate the framework, detailed hydraulic inputs from current drainage models used by sewerage undertakers have been utilised. These inputs include storm and pipe systems, ancillaries, key hydraulic structures, future projections in climate change and population change. The framework provides information on flow capacities that can be accommodated now and in the future. The outputs are presented by assigning a score for the capacity of the network system (explained in Section 2.3). Thus, enhancing the understanding of system performance under current and future drivers such as climate change, population growth, and increase in urban space. This is important as population, urbanisation and climate are all projected to change in the future. Therefore, it is crucial to learn how current drainage infrastructure will respond to future changes.

The motivation for the framework was to drive decision-making and planning of all interventions to improve long term resilience. The CAF programme is also driven by developing a consistent and transparent method to examine the drainage capacity within the UK. However, CAF has received limited exposure within flood research, hence any literature available only describes the generation of the data and guidance for users rather than an analysis of the implications. Since drainage networks are a crucial infrastructure in cities and significant for managing flood resilience, the objective of this paper is to provide a preliminary review and analysis of the CAF within Leeds, UK. Through this analysis, we gain insight into the state of drainage and system capacity within urban areas and improve the exposure of CAF within research and practice more widely.

4.2 Background

4.2.1 Capacity Assessment Framework

All details of the CAF reported within this section have been summarised from the *21st Century Drainage Programme- Capacity Assessment Framework: Project Report* (Gorton et al., 2017a) and the *21st Century Drainage Programme- Capacity Assessment Framework: Guidance Document*(Gorton et al., 2017b). This section is structured to provide a summary of the methods and inputs used to create CAF. This includes a description of:

- drivers that affect the performance of drainage systems now and in the future. E.g., climate change and population growth.
- how scores are assigned for each asset and the aggregate scoring of an area (these are carried out at different scales).

4.2.2 Model Requirements

The framework uses detailed hydraulic models provided by sewerage undertakers (i.e., water companies) (**Table 4-1**). This includes a complete foul system that transports domestic waste and trade flows (i.e., waste flows produced by trade/industry, e.g., car washing establishment) and a storm system that transports rainwater. Additionally, the CAF includes combined sewer overflows (CSOs) that allow emergency discharge into a nearby watercourse for systems that transport both foul and rainwater in the same pipe and are designed to reduce the risk of sewage backing up during high-intensity rainfall. Lastly, the framework includes parameters that have an impact on the system now and in the future such as population, consumption rate, infiltration, and pervious areas.

Table 4-1: Components of an urban drainage system

Input Category	**Description**
Network Data	• Manhole locations, cover levels and chamber floor levels • Pipe locations, dimensions, and invert levels • Network connectivity such as gradient, bifurcation
Ancillary structures	• Combined Sewer Overflows (CSOs) • Pumping stations • Wastewater treatment works • Storage tanks • Control structures (including weirs, sluice gates, orifices, flap valves, outfalls etc.)

4.3 Visualisation

The CAF metric is generated using a hexagonal grid. All analyses and calculations presented have used hexagons, as they represent the curves in catchment boundaries more easily than square grids. Hexagons are preferred over regular square grids because they are more effective in analysing aspects of connectivity (Birch et al., 2007). Additionally, hexagons enable water companies to aggregate personally sensitive data, such as addresses related to customers that would otherwise cause issues with data sharing. Examples of the hexagonal grid maps are provided at different scales **Figure 4-1**. To calculate the CSO and pipe metrics, the total length of sewer within each hexagon is calculated. For this, the CAF counts the sewers that have their centre present within a hexagon (**Figure 4-2**).

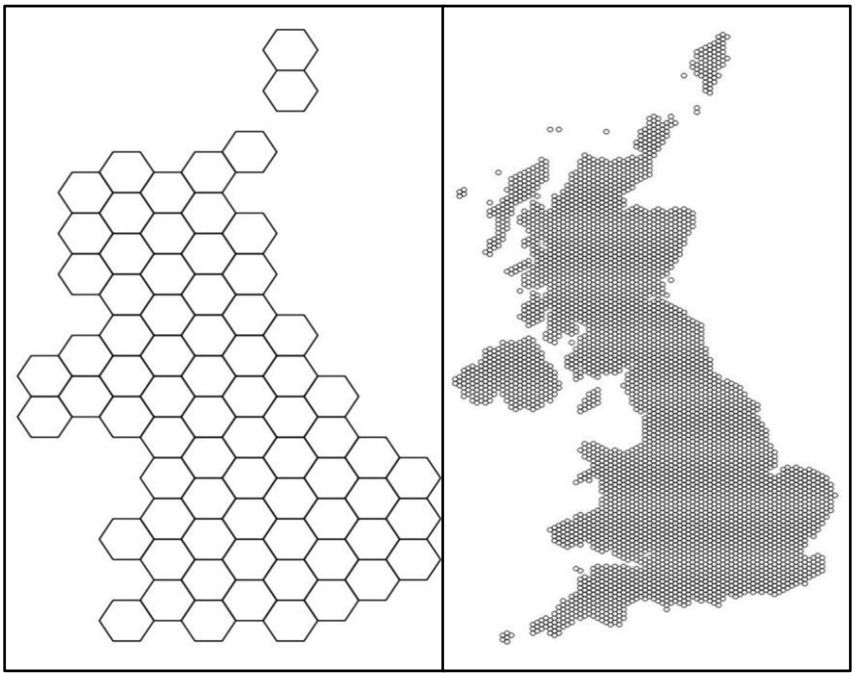


Figure 4-1: Geometric hexagon maps generated by the CAF at scales of 100km and 10km (Gorton et al., 2017a, 2017b; Udale-clarke, 2018.)

Figure 4-2: Demonstrating sewers that have their centre in a hexagon. If a sewer bleeds into another hexagon, it will not be counted.

The CAF establishes scores in two stages. First, the scoring of system performance is assessed by establishing a capacity metric for pipes and CSOs individually. Second, an aggregate score is based on the metrics established in the first stage. There are four factors used to establish metric for pipes and five factors used to establish the metric for CSOs (**Table 4-2**). Summer is defined as June, July and August, as these are the months that usually have low flows in inland watercourses in the UK. The modelling approach used for evaluating asset performance in the CAF uses detailed hydraulic models that are verified, and all owned drainage assets are present in the models. All asset capacity scores are determined using the outputs from the two modelling approaches described in Section 4.2.

Table 4-2: Factors used to establish metrics for pipes and CSO performance.

Pipes	**Combined Sewer Overflows**
Pipe full capacity/dry weather flow (DWF)[1]	Continuation pipe full capacity / DWF
Surcharge Return Periods	Potential of CSO spill[2]
Flooding Return Period	Number of CSO spills per year
Flood volume of the specified return period	Number of CSO spills per summer
	CSO spill volume per year

[1] Dry weather flow (DWF) is the domestic flows and trade flows to wastewater treatment works during a period without rain. DWF = Population*consumption rate + infiltration + trade flows

[2] Spill is defined as discharge in the first 12 hours and any discharge in the next 24-hour block is counted as 1 spill. If there is a 24-hour block with no discharge, the 12 hours and 24-hour block spill counting begin again.

4.3.1 Individual Scoring Metrics

4.3.1.1. Enhanced Method

The enhanced method is used when there is an existing hydraulic model that has a high level of detail and is fully verified. Once a fully calibrated and validated network model has been procured, model simulations are run for return periods of 2, 5, 10 and 30 years. Additionally, CSOs are assessed using individual events from a 3- year time series. The main differences between the initial and the enhanced method are the level of detail included in the hydraulic models, the method in which the individual scores are identified and, the ability to apply high-level interventions to the drainage system. Individual scoring for the enhanced method is identified using the surcharge return period for pipes, the average number of spills per year and per summer for CSOs. The range and classification have been presented in **Table 4-3**.

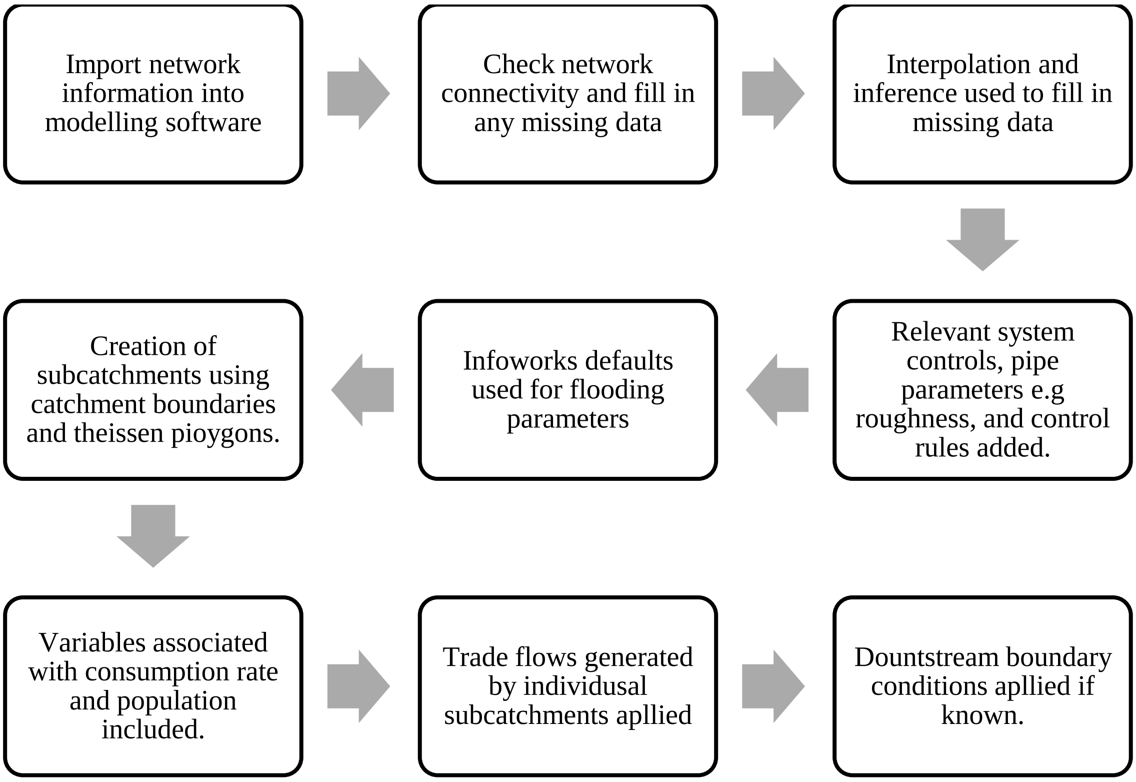


Figure 4-3: Summary of the method used to build an initial hydraulic model as described by the CAF guidance (Gorton et al., 2017a)

Table 4-3: Scoring metrics for pipes and CSOs used in the initial and enhanced methods

		Range			**Points**		
	Enhanced method						
Pipe	Surcharge Return Period (Years)	>10	>2 but <10	≤ 2	0	1	2
CSO	Average number of Spills per year	≤ 20	>20 but ≤40	>40	0	1	2
	Average number of spills per summer.	≤ 3	>3 but ≤10	>10	0	1	2

4.3.2 Aggregating Scoring

The second stage of scoring is the aggregate scores, which are calculated by the percent length of individual pipes classified as red pipes per hexagon based on the metrics provided in **Table 4-3**. Red pipes are defined as pipes that surcharge in a 1 in 30-year storm event. There are three methods in which aggregate scores can be calculated and applied for pipes and CSOs. These are:

$$Length\ of\ pipe = \frac{Total\ Length\ of\ pipes\ with\ a\ RED\ individual\ score\ x\ 100}{Total\ Length\ of\ all\ pipes}$$

Equation 11

$$Population\ equivalent = \frac{Population\ equivalent\ upstream\ of\ all\ red\ pipes\ x\ 100}{population\ equivalent\ upstream\ of\ all\ pipes.}$$

Equation 12

$$CSO\ Scoring = \frac{Total\ number\ of\ points\ scored\ by\ CSO\ x\ 100}{Total\ number\ of\ CSOs\ x\ 2}$$

Equation 13

Using equations 9, 10 and 11, aggregate scores presented as percent risk are then established, where 0% represents missing data, this classification is presented in **Table 4-4**. This means that for a hexagon that is identified at level 5, 60 to 100% pipes within that hexagon will surcharge for a 1 year or 1-in-2-year return period.

Table 4-4:Aggregate score assigned to a hexagon

Risk Level (Aggregate Score)	% Length of pipes at red length
1	0-15
2	15-30
3	30-45
4	45-60
5	60-100

4.4 Drivers

The individual and aggregate scoring include representation of drivers that affect drainage network performance, both now and in the future (**Table 4-5**). Present-day drivers are those parameters that currently affect system performance and capacity, most of the parameters are based on the existing hydraulic models of the region. Key present-day drivers are:

1. Dry weather flows (DWF), are represented as:

   *DWF = Population * Consumption Rate + Infiltration + Trade Flows*

   whereby population and consumption rate for a region are provided by sewerage undertakers and from current hydraulic models. Generally, the Water Resource Management Plan (WRMP) is used as guidance for any population projections. Infiltration is considered only if the sewerage undertaker provides an existing hydraulic model and, depending on the characteristics of the region, an appropriate infiltration rate is selected. Trade flows are used to represent flows produced in a location where trade or industry processes are carried out e.g., vehicle washing, food and drink manufacturing.

2. Rainfall data is only applied to the enhanced model to determine the runoff response of the drainage system. Both design storms and time series rainfall (TSR) are used to assess the runoff response of the drainage system. For the CAF, location-specific time series of 3 years is used, and if this is not available, a representative 3 years is utilised. All events that are less than 3mm in depth or where intensity is never greater than 3 mm/hr are excluded. Design storms for the return period of 2, 5 10 and 30 years are used for 30 mins and upwards to capture the critical duration of all pipes.

Future drivers are those parameters that have the potential to affect the performance and capacity of the drainage system in the future. Four key conditions are considered for the assessment of future drivers on the drainage system. These are:

1. Population changes due to growth and development, where the CAF modifies the current population based on the projection provided in the UK's Water Resource Management Plans (WRMP). This is done for a 5-year and 25-year time horizon. Sensitivity testing is also carried out by applying a +30% and -30% to the population uplift (or reduction).
2. The consumption rate increase is applied based on growth in population and the average rate provided by the sewerage undertaker.
3. Urban Creep is the decrease of permeability in existing urban areas, this has been applied using the method described in Allitt (2009) which focuses on applying an algorithm to property density within an area to calculate the average increase in impermeable area per property per year. Urban creep uplifts are only applied if the percentage permeability of an area is less than 80%. Sensitivity testing is carried out by applying a +30% and -30% to the estimated urban creep for the 25-year horizon.
4. Climate change uplifts have been applied using the UKCP09 climate change projections. A 40% uplift for the 2100 epoch has been applied to the design storms. For sensitivity analysis, the design storms were adjusted by +/- 30% and the P90 and P50 high emissions scenario and P50 for medium emission scenarios have been applied to the time series.

Table 4-5: Approach in which present and future drivers are represented in the initial and enhanced method to generate the CAF outputs.

	Description of Driver	**Initial Method**	**Enhanced Method**
Present Day Drivers	Population and consumption	Based on open-source GIS and census data	Based on modelled values provided by the Sewerage undertaker
	Infiltration	N/A	Based on modelled values provided by the Sewerage undertaker
	Trade Flows	Estimated based on consented discharges or metered businesses	Based on modelled values provided by the Sewerage undertaker
	Rainfall (design and time series rainfall)	N/A	Based on the time series provided by Sewerage undertaker
Future Drivers	Population Growth	Modified using the WRMP for 25-year and 5- year time horizon	Based on values used by Sewerage undertaker
	Consumption Rate	Future average household per capita should be estimated for the 25-year and 5-year time horizon as outlined in the WRMP	Based on values used by Sewerage undertaker
	Urban creep	Allitt et al (2010) method applied for 25-year time horizon	Allitt et al (2010) method applied for 25-year time horizon
	Climate change		UKCP09 uplifts

4.5 Summary

To summarise, the generation of the CAF data includes 3 main steps these have been outlined in **Figure 4-4**.

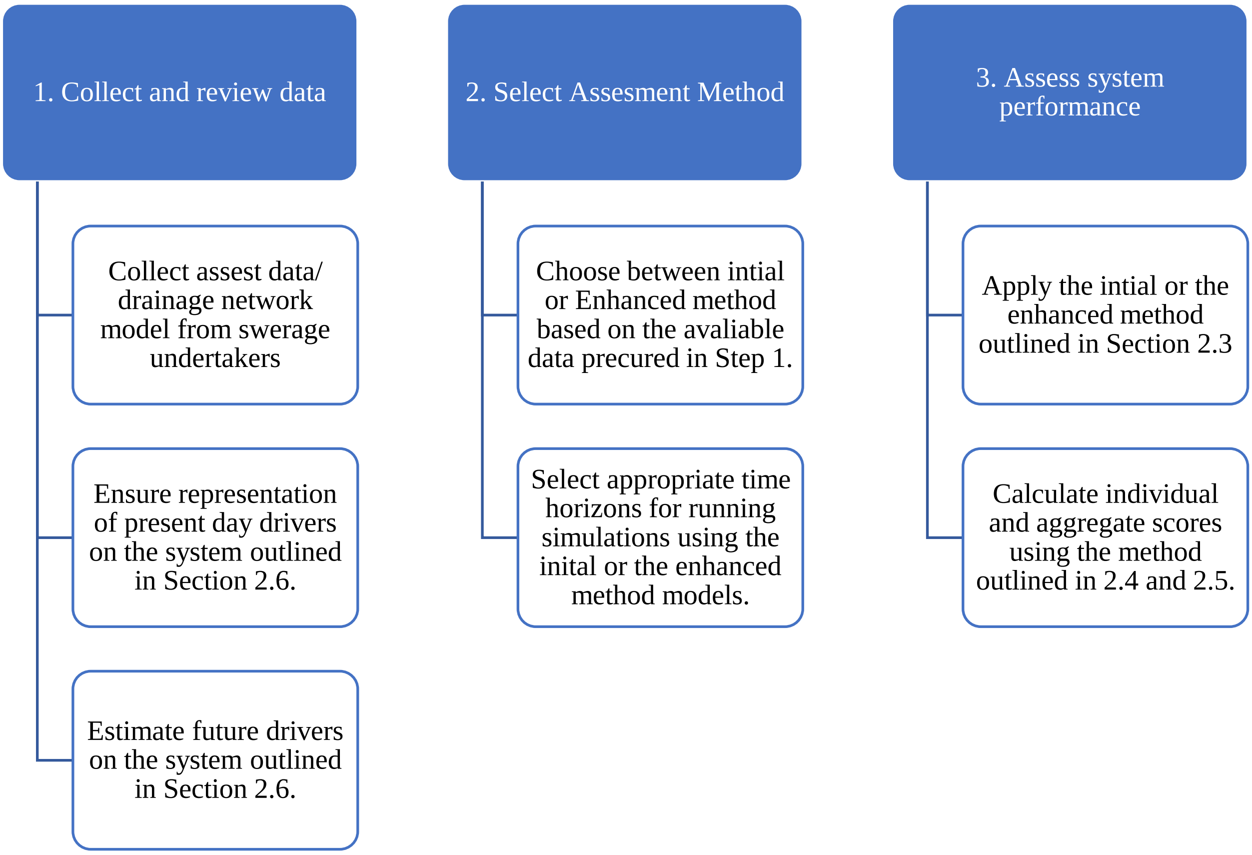


Figure 4-4: Three key steps for the generation of the CAF data as described by (Gorton et al 2017a, 2017b and Udale-Clarke, 2018).

If the enhanced method is utilised, two additional steps can be applied these are the ability to include steps that apprise interventions and plan and implement investment strategies. The key focus of this paper is the aggregate score that indicates drainage network performance and capacity. Sections hereafter present the analysis of the CAF outputs, i.e., the aggregate scores, for Leeds, UK.

4.6 Materials and Methods

This section describes the methods used to analyse the CAF data provided by Yorkshire Water. The CAF dataset provided by Yorkshire Water for Leeds was generated using the Enhanced method described in Section 4.3.1.1. To review and analyse the CAF, a combination of open-source packages were used. Namely, QGIS for geospatial analysis and mapping, and Python Arcpy packages were used for additional spatial analysis. ArcPy is a Python package that allows GIS scripting to perform spatial data analysis and automation.

4.6.1 Case Study: Leeds.

Leeds, located in West Yorkshire, is a major urban city in the North of England. Present-day Leeds is a conglomerate of its surrounding towns, such as Morley, Pudsey, Rothwell, Weatherby and Yeadon.

Five rivers run through or along the administrative boundary of the city, namely the Wharfe, Ouse, Aire, Nidd, and Calder. Leeds can be further subdivided into 46 sub-catchments, which cover a total of 750km^2 (**Figure 4-5**). Leeds has a rich history in piped systems and is one of the first towns to have a piped water supply in Britain. Around 1846, trunk sewers that ran along the river, with waste and stormwater discharged into the river, were established. From 1846 to the 1900s sewer construction proceeded at the rate of 193 km per decade. It was not until the late 1900s that storm sewers were introduced to deal with surface water drainage (Sellerts., 1997).

The population of Leeds in 2020 was estimated at just under 800,000 and it is projected to increase (Park, 2020). Even with recent legislation restricting new development to greenfield runoff rates, it is inevitable that increase in runoff can be expected with urban creep and densification as well as overloading of existing aging and undersize sewerage trunk mains designed for smaller urban areas. This, combined with increase in magnitudes and frequency of extreme events due to climate change will overburden current stormwater systems. Consequentially resulting in an increasing number of locations experiencing flooding, and an increase in the number of people that are exposed to flood hazards. Leeds is estimated to contain a total of 485,239 properties, of which 18,446 properties are at risk of flooding from both internal (wastewater enters property) and external sewers (flooding within property boundary but not in the property itself). It is estimated that a total of 39,299 will be exposed to internal and external sewer flooding by 2080 (Yorkshire Water, Private Communication, 2022).

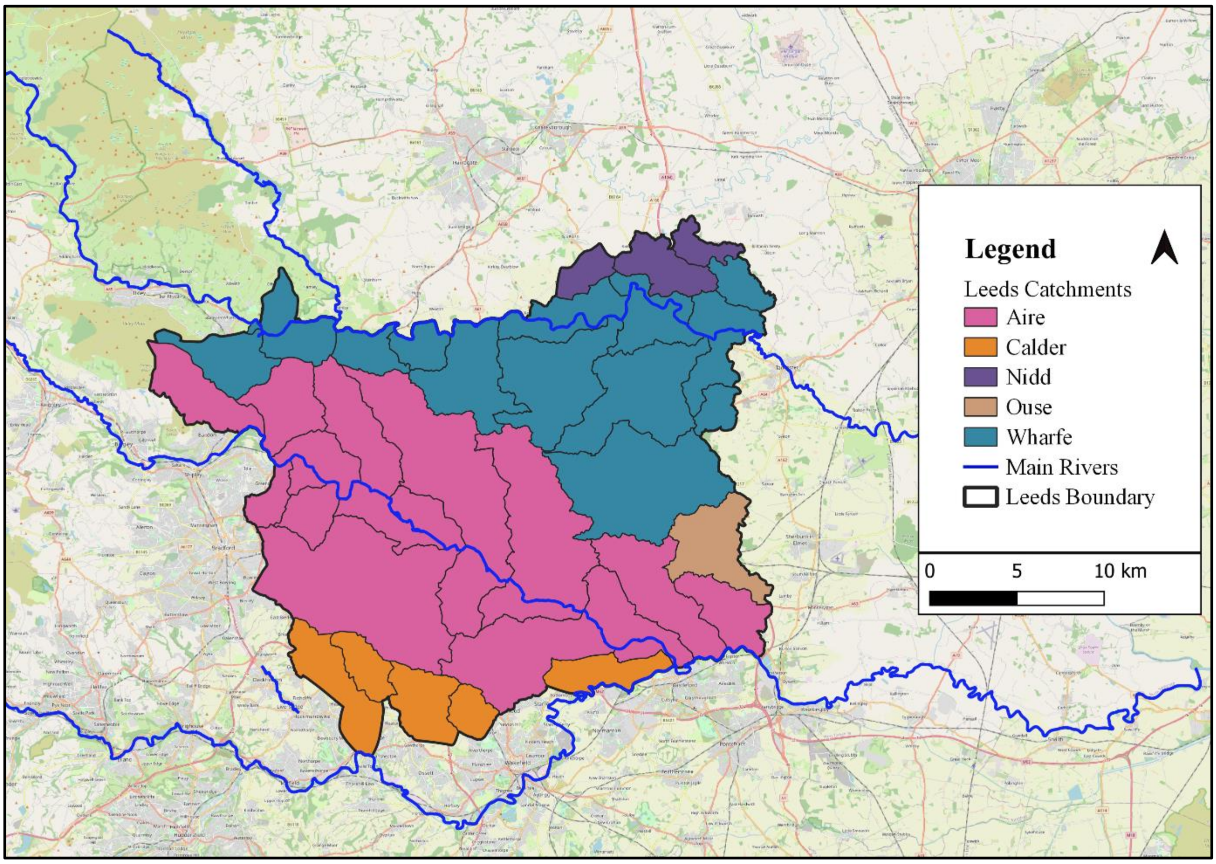


Figure 4-5: Leeds geographical boundary and the five main catchments that drain into rivers in Leeds.

4.6.2 Data

The CAF data provided by Yorkshire Water was in GIS compatible shapefile format and processed using QGIS. A set of capacity hexagons clipped for the whole of 736 km^2 of Leeds was provided. Attributes of each hexagon are a unique hexagon ID number, number of properties per hexagon, total length of the sewer, red length for the total sewer for the epochs 2020, 2030, 2050 and 2080, a score metric of the red length pipes, and a risk matrix category (**Table 4-6**). Each hexagon has an area of 0.5 km^2.

Table 4-6: Data provided by the CAF

Column Title	**Description**
Grid ID	Unique Hexagon Number
Properties	Total number of properties within Hexagon
Total Length	Total modelled sewer length (m) contained in a Hexagon
Red Length	Total Red Sewer Length (m) for 2020, 2030, 2050 and 2080.

Individual Score	(Red length /Total Length) x 100
Aggregate Score	The scoring mechanism that assigns a risk level 1 if the score for a hexagon is 0 – 15% and so on.

4.6.3 Local Spatial Autocorrelation (LSA)

Anesilin Local Moran's clustering and outlier analysis referred to LSA in this paper help identify where the clusters and outliers are located. This is where analysis of the data set identifies clusters of high and low values by examining the feature individually and establishing a neighbourhood within the dataset (Mitchel, 2005; Dubin, 1998; Getis and Ord, 1992). The two main questions answered with the analysis are:

1. Is this feature significantly different from all other features in the given dataset?
2. Is this neighbourhood significantly different from all other neighbourhoods within the given dataset?

The significance of the outputs is divided into four clusters, High-High (HH), Low-Low (LL), High-Low (HL) and Low-High (LH), also see **Figure 6.**

Local Moran's clusters and outliers are calculated using Equation 14:

$$I_i = z_i \Sigma_j w_{ij} z_j$$

Equation 14

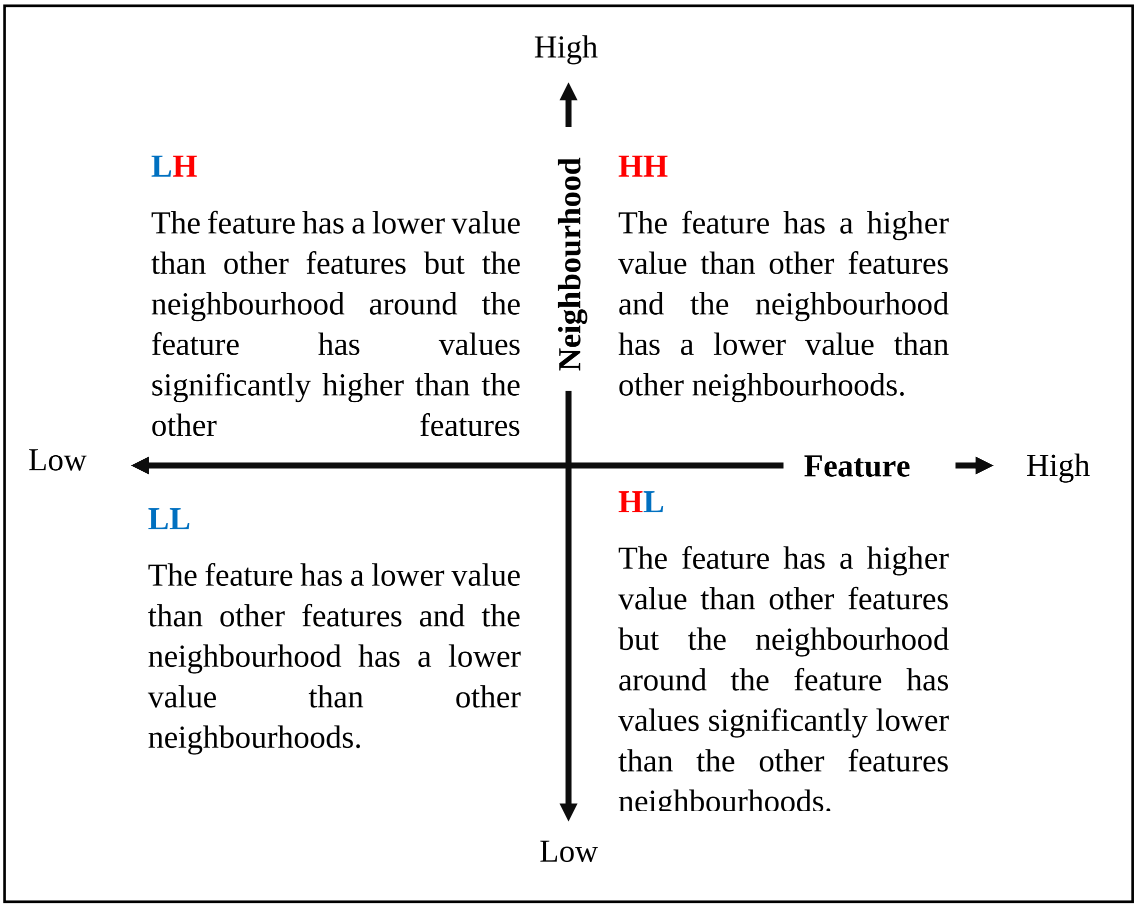
Where:

zi and *zj* are the observations in deviations from the mean and,

wij is the spatial weight matrix element.

Positive values of *I* suggest that there is a spatial cluster of similar values and negative values represent a spatial cluster of dissimilar values

The significance of the clusters is generated using 9999 random permutations of the input data set which, for this paper, is the aggregate scores generated by the CAF This quantity of permutations was selected as it is usual practice and considered as robust. A map showing the location of these outliers and clusters is then generated with the topology of the four clusters identified in **Figure 4-6**. For clustering analysis, it is also important to conceptualise spatial relationships, and there are several methods available to do this, such as contiguity, K nearest neighbours, and zone of indifference (Rodriguez et al., 2021). Here, the inverse distance was used with a default threshold band. The inverse distance conceptual model is a method for conceptualising spatial relationships and model processes where the closer two features are in space, the more likely they are to influence each other. So, to the extent of the study area, all features within the data set influence other features, i.e., all features are a neighbour to other features. The Local Moran's cluster and outliers' analysis and mapping were conducted using Arcpy packages, i.e., GIS packages, in Python.



The feature has a lower value than other features but the neighbourhood around the feature has values significantly higher than the other features

The feature has a higher value than other features and the neighbourhood has a lower value than other neighbourhoods.

The feature has a lower value than other features and the neighbourhood has a lower value than other neighbourhoods.

The feature has a higher value than other features but the neighbourhood around the feature has values significantly lower than the other features neighbourhoods.

Figure 4-6: : The four significances of clusters and outliers using the Local Moran's Autocorrelation Analysis, with feature risk plotted on the x-axis and neighbourhood risk plotted on the y-axis.

4.7 Results

4.7.1 Red Length

The total length of sewers modelled for Leeds is 4905.33 km, this averages at 981.06 km per hexagon. **Figure 4-7** (A, B, C and D) show the locations of red length sewers in Leeds from 2020 to 2080. Red length pipes refer to the pipes that are surcharged in a 1 in 30-year return period. Although from it is not clear from **Figure 4-7** if there is a significant change in the length of sewers that surcharge, **Table 7** summarises Red Length per catchment for the four epochs where, we can observe the percentage of pipes that are classified as red length and the percentage increase in those classed as red length from 2020. Additionally, Figure **4-8** shows the length increase of the red length pipes, average increase in red length for the 2030 epoch is 164.71 km, for the 2050 epoch it is 296.01 km, and for the 2080 epoch it is 497.63 km. For the entire city of Leeds, Red Length sewers stand at 17.63% in 2020, 21.11% in 2030, 23.90% in 2050 and 28.16% in 2080 relative to the total length of modelled sewers. The percent increase in red length sewers from 2020 is 19.7%, 35.50% and 59.69%, respectively.

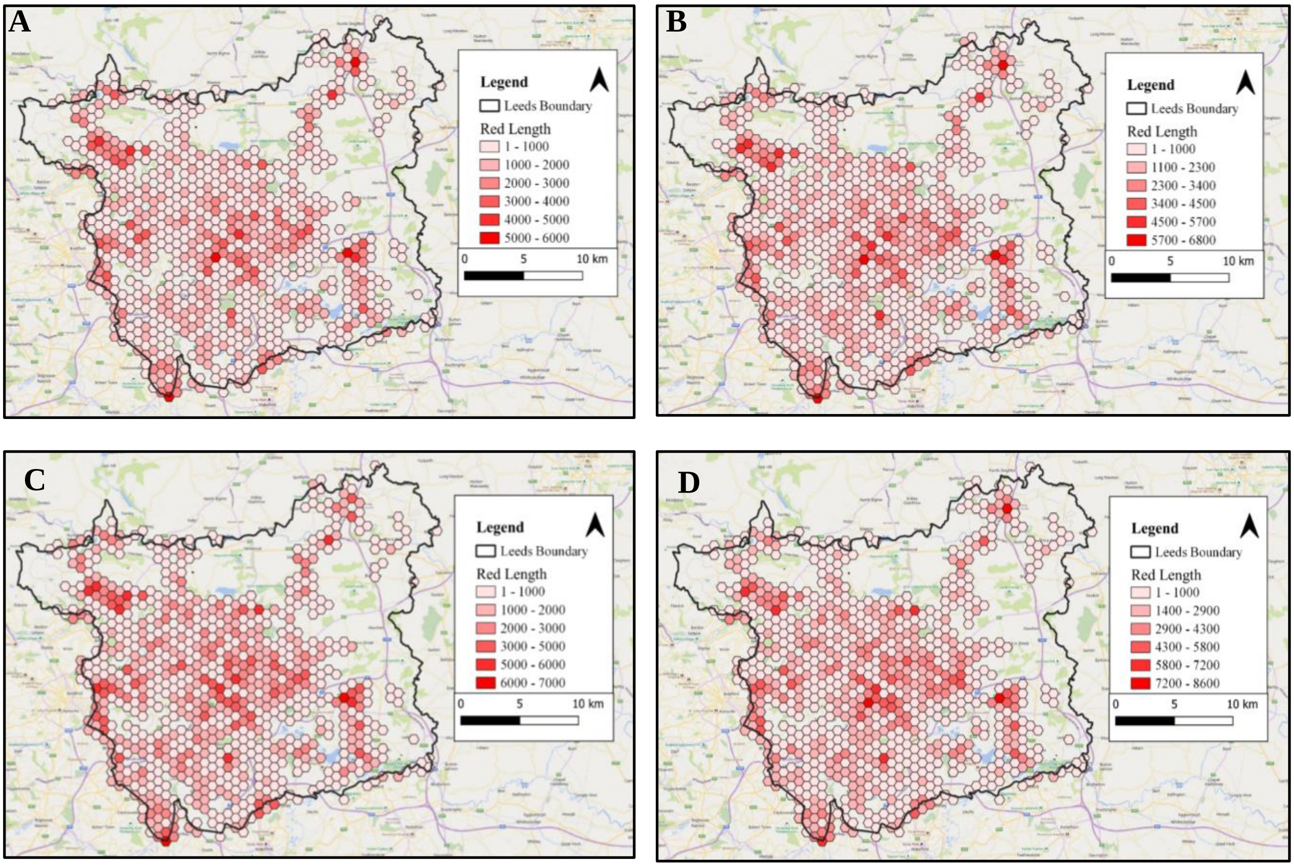


Figure 4-7: Red length for the epoch 2020 (A), 2030 (B), 2050 (C) and 2080 (D) for the city of Leeds

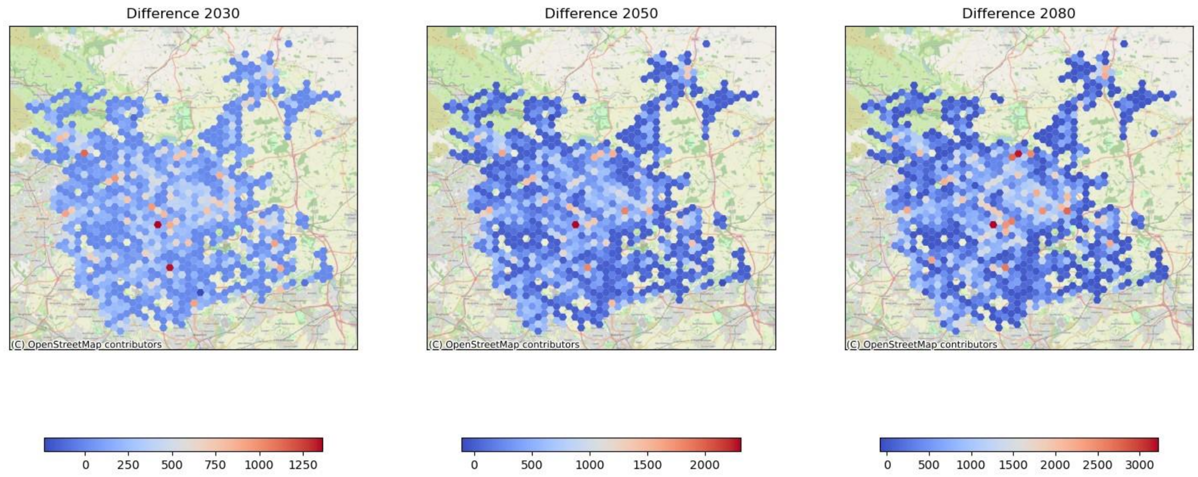


Figure 4-8: Plots showing the increase or decrease in the red length of the pipes in each hexagon with 2020 as the baseline year.

Table 4-7: Length of pipes identified as Red Length of pipes for the city of Leeds

Epoch	**Red Length (km)**
2020	865.19
2030	1035.97
2050	1172.41
2080	1381.645

4.7.1 Aggregate Scoring

Error! Reference source not found. **Figure 4-9** and **Figure 4-10** (A, B, C and D) present the aggregate scores per hexagon in Leeds. The aggregate capacity scoring metric is calculated using the methodology outlined earlier in this Chapter. Each hexagon is assigned a score from 1 to 5 which indicates the percent of pipes that are likely to surcharge within a hexagon. The five risk levels are assigned based on the length of pipes that are identified as red length (**Table 7**). By 2080, it is estimated that 82.5km^2 of Leeds will contain pipes that surcharge in 1 in 30-year storm event. In 2020, 2030 and 2050 the area of Leeds identified as risk level 5 are 52.5km^2, 64km^2, and 66.5km^2, respectively. 2080, 18% of Leeds will contain over 50% length of pipes that are identified as red length.

Although the maps in **Figure 4-9** suggest that not much changes in the overall scoring of the hexagons, the breakdown of the scores themselves demonstrates otherwise. For instance, the number of hexagons in Leeds that score at risk level 1 decreased by 40.70% from 2020 to 2080. Additionally, hexagons that are classified as risk level 3 increase by 75%. Risk level 4 has the greatest increase (140%) in the number of hexagons identified, lastly, the number of hexagons identified as risk level 5 increased by 57.14% from 2020 to 2080. Overall, the risk of surcharge increases under future drivers.

The minor trend of risk increases the decreases for risk level 2 appears as an anomaly, the trend is that the number of hexagons identified as risk level 2 increases by 4.04% in 2030 and 2050 and then decreases by 2.02 %.

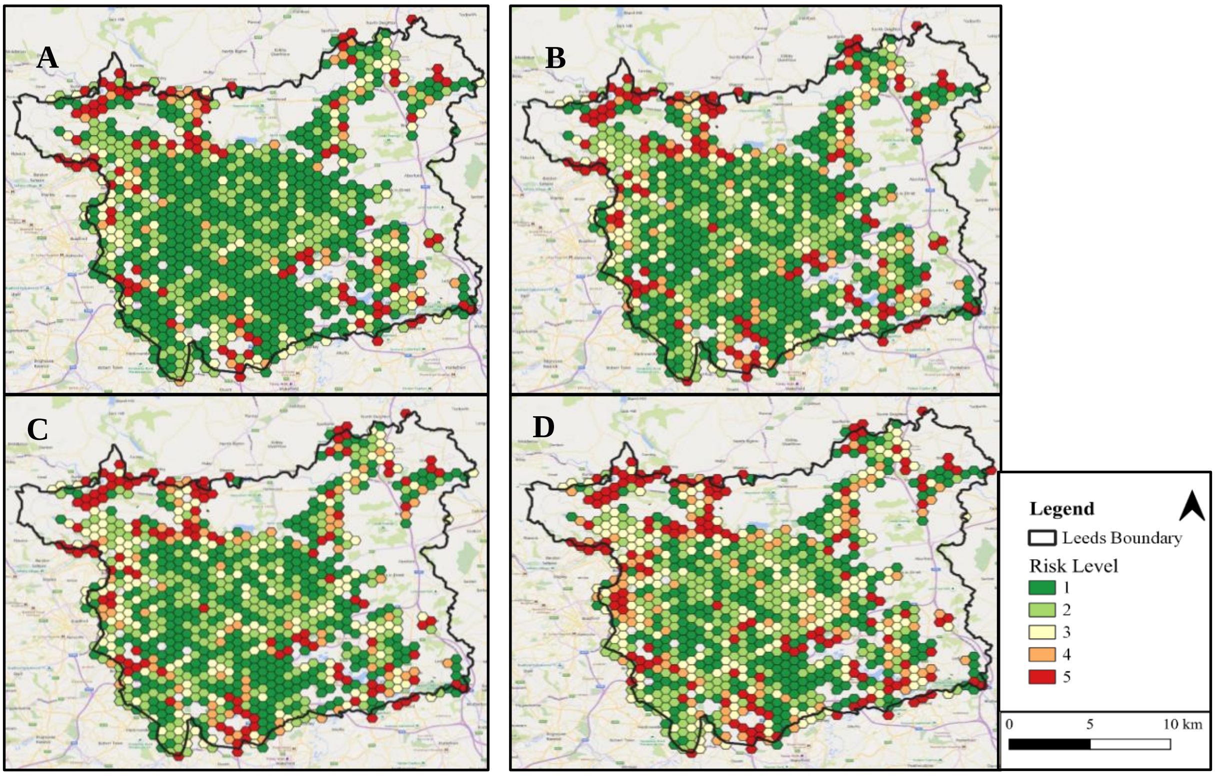


Figure 4-9:Aggregate hexagon score for Leeds, for the 2020 (A), 2030 (B), 2050 (C) and 2080 (D) epoch

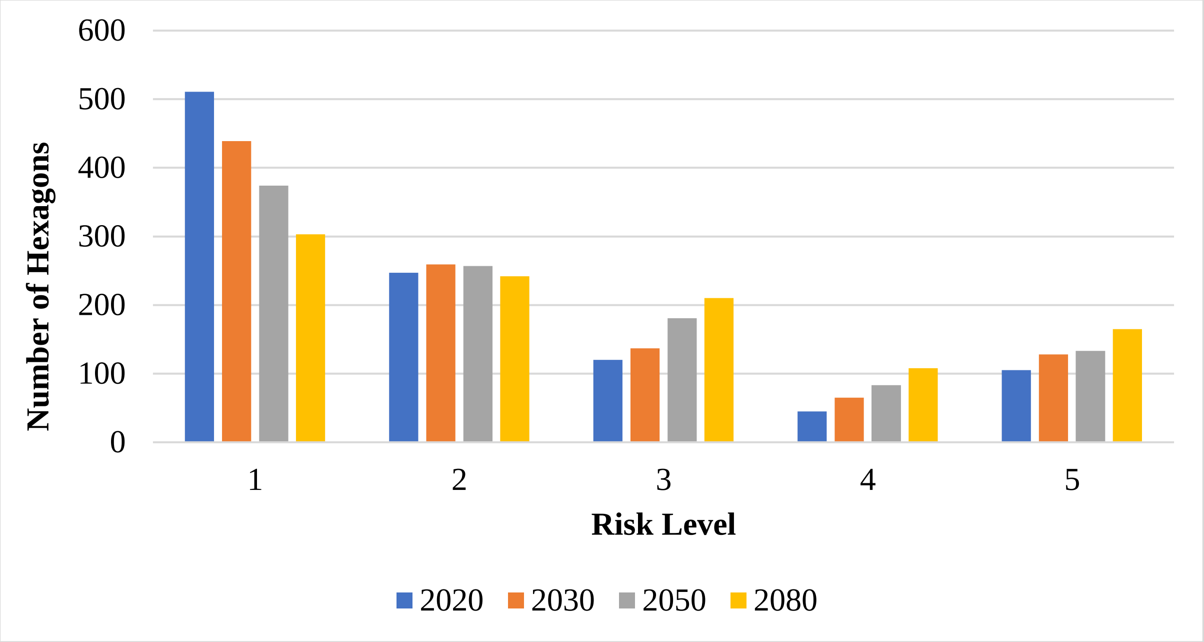


Figure 4-10: Number of hexagons identified as risk level 1 to 5 for the epochs 2020, 2030, 2050 and 2080

4.7.2 Spatial Autocorrelation

Figure 4-11 and **Figure 4-12** (A, B, C and D) provide a summary of the Local Moran's clusters and outliers for the CAF scores per hexagon. Local Morans help understand spatial variability in a given data set. The significance of the outputs for the Local Morans analysis is divided into four clusters. Based on the maps in **Figure 4-12**, HH clusters are spatially distributed around the edges of the catchment, with a significant large cluster located in the northwest and LL clusters. The HH and HL clusters increase from 2020 to 2080, whereas the LH and LL clusters decrease. The maps in **Figure 4-12** also demonstrate that several hexagons identified as LH outliers are changed to HH clusters by the year 2080. Furthermore, the density of HL outliers in the centre of the Leeds city boundary increase in the future years, reducing the number of hexagons identified as LL clusters. The spatial pattern between the Aggregate Scoring risk maps and the LSA maps presented in this section are similar, however, the LSA maps make the spatial variability more obvious. Generally, the Local Moran's Index for each hexagon ranges from -0.4 to 0.6 for all the epochs. The HL and LH outliers have a negative Local Morans Index and the HH and LL clusters have a positive Local Morans Index.

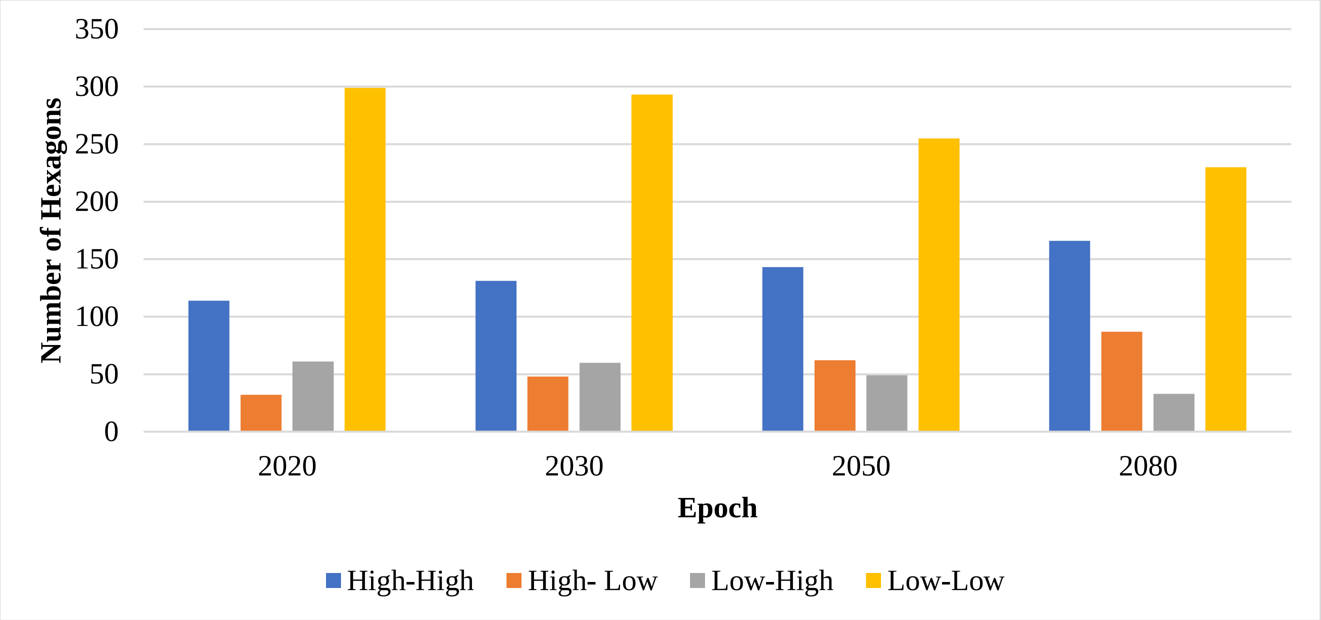


Figure 4-11:Number of hexagons identified as Local Morans clusters and outliers for the epochs 2020, 2030, 2050 and 2080

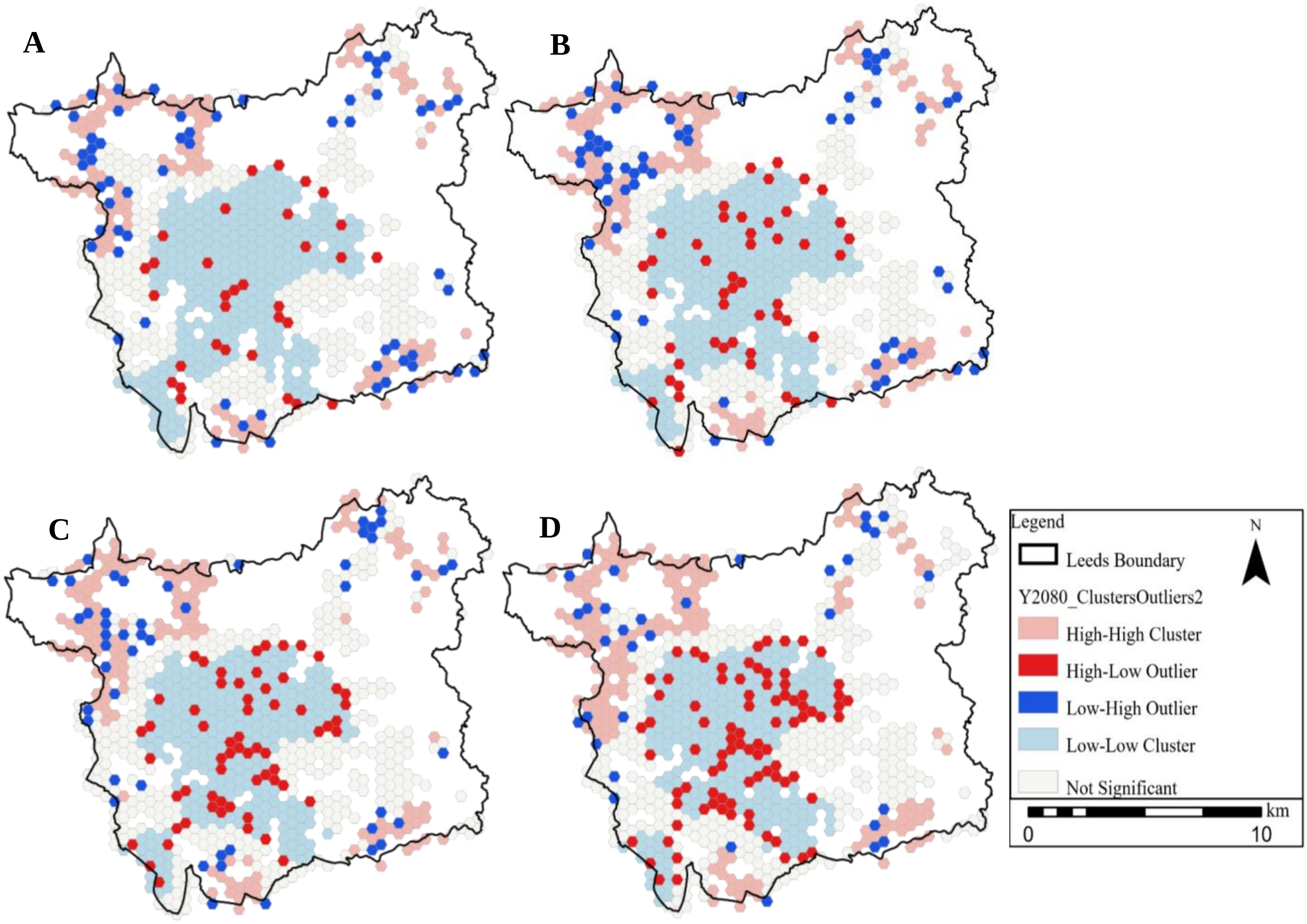


Figure 4-12: Local Morans significance for the hexagon risk scores for the epochs 2020 (A), 2030 (B), 2050 (C) and 2080 (D)

4.8 Discussion

A significant spatial clustering was identified through mapping and LSA for hexagons that are identified as risk levels 1 and 5 as shown in **Figures 4-7** and **Figure 4-9**. Most of the low-risk hexagons are located within the centre of the Leeds boundary. This is expected as these are urbanised areas, hence are likely to have a higher density of internal and external sewers. Additionally, they are able to accommodate a higher capacity of incoming domestic and storm flows. By 2080, a significant number of hexagons within the centre of the boundary are classified as either risk level 2 or 3. This suggests that 15% to 45% of pipes and CSOs within these hexagons are likely to surcharge during a 1-in-10-year event or lower. Hence, urban resilience to sewer flooding will be reduced in the future based on the CAF aggregate scores due to drivers identified in Section 2.4. This is further confirmed by the LSA maps in **Figure 4-12** that used the Local Moran's cluster and outlier analysis to identify patterns within the CAF dataset for Leeds.

Using LSA we gain insight into the spatial distribution of the hexagons and risk levels and understand how the risk levels are spatially clustered within Leeds from 2020 till 2080. The LSA maps in **4-12** demonstrate that the proximity of high-risk level to low-risk level hexagons changes the classifications for the worse. Hence, if a hexagon is identified as high risk in the present, it is likely that the risk levels of the surrounding hexagons will also increase when looking at drainage capacity in the future. This is especially evident for the northwest of Leeds, where hexagons identified as LH outliers in 2020 were identified as HH clusters by 2080 (**Figure 11 (A) and (D)**). Additionally, the centre of Leeds sees a significant number of HL outlier hexagons. The location of the HL outlier hexagons in 2080 are hexagons that neighbour HL hexagons in 2020. The application of LSA has established a spatial link between hexagons that currently perform poorly and those that will underperform in the future. The outlier hexagons provide a good starting point for investigating the spatial implementation of flooding interventions to improve resilience to extreme events as well as complement the capacity of the local drainage system. In this context, the spatial implementation of sustainable urban drainage systems (SUDs) is important. For example, Rodriguez et al (2021) found a positive correlation between the location of SUDs implementation and the improvement in resilience toward sewer flooding.

The location of the HL and LH outliers provides an opportunity to investigate how and why the capacity of a hexagon connects to another. One potential explanation for the link between hexagons performing poorly now and in the future is that the pipes underneath the hexagons are part of the same subsystem. Due to pressures such as increased extreme events in the future, the length of the system that exceeds capacity is increased. LSA shows the inherent connectivity of the network, which is not explicitly presented when mapping the scores. The LSA also potentially demonstrates critical locations where systems are older or where there is a lot of development, putting the existing mains they connect to under more pressure. Although doing so is not within the scope of this paper, it highlights that visualising the capacity of the drainage system in hexagons has the potential to enable the analysis of the CAF data in fragments. For instance, high-risk classified hexagons may capture more attention from potential users, although the underlying model is a detailed web of continuous pipes and ancillaries for a given area that runs across several hexagons. However, the end-users such as local authorities, modellers, and practitioners, of the CAF do not have access to this visualisation, hence, focus may be given to high-risk level hexagons without considering their relationship with neighbouring hexagons.

Both the aggregate score maps and the LSA maps provide insight into the spatial variability associated with the drainage capacity. Maps in **Figure 4-9** and **Figure 4-12** show that the capacity of the drainage system is highly variable from one hexagon to another, this spatial variability is consistent through all the epochs. Although it is known that drainage capacity is a spatially variable, the CAF allows visualisation of this variability. This is useful when investigating methods to represent drainage networks in flood models on a coarse or a fine scale. As previously stated, the current method used to represent drainage infrastructure in the flood model is a simple rainfall reduction approach, which assumes that flows equivalent to either a 1-in-10 or 1-in-30-year event is the capacity of the drainage system in all places (Chang et al., 2015; Vercruysse et al., 2019). However, utilising the CAF provides additional information on how the drainage system performs within an area and enables the visualisation of connectivity within the study area. This enhances the ability to quantify the performance of drainage systems with better accuracy by identifying locations where the network is underperforming, which will be a useful tool to consider when generating rainfall inputs for flood models.

The maps show that a significant part of the city either had no model or no data for initialising and establishing the CAF. A total of 534 hexagons or 267 km^2 of the city has missing data, this accounts for 36.25% of the city of Leeds. This provides an incomplete account of the performance and connectivity of the drainage system within the city of Leeds. Therefore, the data presented in this paper provides an incomplete picture for decision making and long-term planning related to sewer systems in these areas. Nonetheless, a significant area of Leeds has sewer models, therefore the data presented can still be used to design interventions at a high level. For instance, CAF can be used to estimate the impact of increasing SUDs in hexagons that have high-risk levels and estimate costs of increasing green space in selected hexagons.

The subject of the absence of sewer modelling data however is not limited to this paper, to date, only 25% of the surface water sewers in England and Wales have been modelled. For Yorkshire, the total percentage of surface water sewers currently modelled is only 30% (Udale-clarke, 2018). Therefore, an obvious effort needs to be made to improve the coverage of models to generate complete CAF datasets. It is also important to note that some pipes are designed to surcharge significantly (without causing flooding), and the CAF does not omit these pipes from the red length modelled, therefore some hexagons identified as high-moderate to high risk may have a lesser risk score in a risk sense. Additionally, it is unknown if the risk in a specified hexagon is due to the foul, combined or storm drainage system. Hence, when applying engineering or economic interventions, it is important to consider unknowns and uncertainty associated with the CAF inputs and outputs.

The results presented suggest that the capacity of the drainage system in Leeds will deteriorate using UKCP09 outputs. Using the recent UKCP18 projections will likely result in a higher number of hexagons being classified at high-risk levels suggesting a worse fate for the capacity of the drainage system within Leeds, as the frequency of extreme events is projected to increase. The UKCP18 climate change projections are of enhanced spatial resolution (2.2km) than UKCP09, hence have the ability to represent small-scale or local behaviours in the atmosphere (Met Office, 2019). This is crucial when simulation atmospheric convection which lead to intense storm events. The

Environmental Agency guidance for rainfall uplifts for the region of Aire, Calder, Whare and Lower Ouse is 20% central allowance and 35% upper end allowance for the epoch 2050. For epoch 2070 the uplift allowance changes to 25% for the central allowance and 40% for the upper end allowance (Met Office Hadley Center, 2019).

Overall, the CAF provides a method of scoring network performance and capacity, even in locations where a hydraulic network model is lacking in detail, through the initial method of calculating individual and aggregate scores. For Leeds, the enhanced method was used i.e., detailed hydraulic inputs, while this is ideal, there are several advantages and disadvantages of both the enhanced and initial method, these have been outlined in **Table 4-8.**

Table 4-8: Advantages and disadvantages of the initial and enhanced method used for individual and aggregate scoring of the CAF

Method	Advantages	Disadvantages
Initial	• Provides some understanding of drainage capacity in locations where models are not of good quality. • Fewer data requirements than the enhanced method	• Potential to underestimate DWF as infiltration is neglected • Does not include contributing areas and thus does not provide information on rainfall response related to system performance and future drivers
Enhanced	• Robust and reliable as they contain detailed hydraulic inputs • Provides information on rainfall response related to future drivers • Allows application of investment strategies and estimation of costs associated with the strategies.	• Requires detailed hydraulic inputs that may not be available for every location • Requires a higher number of model simulations

4.9 Conclusions

Drainage systems are vital infrastructure for the operation and resilience of a city. The main role of drainage infrastructure in the UK is to transport domestic waste and stormwater to WWTP. Even though drainage systems are an integral city infrastructure, outside the operational management of these assets little is known about their performance and capacity for risk assessments and strategic and planning purposes. This paper analysed the Capacity Assessment Framework outputs to understand the drainage network performance for the City of Leeds, UK.

Our analysis of the CAF outputs for Leeds has found that generally, the capacity of the drainage system within Leeds will decrease, this is a consequence of climate change, population increase, and urbanisation. Although the exacerbation of the capacity of drainage infrastructure is a known fact, this paper uses the CAF outputs to provide quantified evidence in support of this claim. Using the LSA helped identify spatial patterns within the dataset. It was found that within Leeds, hexagons that are high risk in 2020 have similar properties to the performance and capacity of the drainage systems of the surrounding hexagons, indicating that the proximity of a hexagon that has poor capacity is important, and will indicate similar performance of pipes in surrounding hexagons.

The capacity assessment framework could be improved by updating the climate change projections and improving the coverage of sewers, however despite these shortcomings, the framework provides a new and excellent opportunity for practitioners and researchers in the field of hydrology and urban planning. The framework can be utilised to improve the implementation of SUDs and estimate costs for implementing interventions now and under future scenarios. Furthermore, the framework could prove to be especially important in improving inputs into flood models to better represent spatially varied drainage infrastructure. Overall, the CAF outputs can be used as a tool to spatially prioritise locations where practitioners and stakeholders need to prevent negative environmental impacts associated with drainage performance and improve the resilience of any current or new developments

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Chapter 5 Drainage Representation in Flood Models: Application and Analysis of Capacity Assessment Framework

Abstract

Drainage systems are an integral part of urban infrastructure to help transport and treat wastewater as well as manage flooding during extreme rainfall events. Although there is a significant cost associated with the creation, operation and maintenance of drainage systems, the representation of these systems in flood models is overly simplified. This simplification is due to data protection regulations, and the complexities associated with drainage network modelling. A new framework developed by Water UK in collaboration with the Environmental Agency and sewerage undertakers for UK Drainage Water Management Plans provides data on the capacity and performance of the drainage system. The output from this framework provides a new method of incorporating a more explicit representation of spatially varied drainage capacity in flood models.

This study presents the first application of the UK's capacity assessment framework (CAF) for drainage representation in flood models. We develop a method of using the CAF outputs to represent spatially varied drainage losses across a catchment and assess its impact on flood risk. Three catchments in Leeds are used to quantify the difference generated in flooding when using a national average removal rate (NARR, e.g., 12mm/hr) and our CAF-derived rainfall removal rates. Although there is variance across catchments, the results show the CAF removal rates increase flood depths, velocities, and flood hazards when compared to the national average due to a more realistic representation of the real system drainage capacity. With the pressures of climate change and continued urban development, a better representation of real drainage systems capacities will become more important and will make local solutions more resilient and relevant to the realities on the ground.

5.1 Introduction

Drainage systems are a key infrastructure to convey, collect and store water. Increases in population and hence urbanisation have led to the replacement of natural processes of drainage, such as infiltration, with infrastructures such as pipes, and culverts, as well as forms of sustainable urban drainage systems (SUDs) (Booth, 1991; Bisht et al., 2016; Butler et al., 2018). Over time, drainage systems developed from a simple ditch or gully on the side of a path into a complex network of underground pipe systems. These pipe systems are often designed to convey and treat either: (i) foul water, i.e., waste produced at homes; or (ii) stormwater, i.e., excess water because of extreme rain; or (iii) a combination of both, through combined systems (Smedema et al., 2004; Butler et al., 2018).

Pipes that make up a drainage system vary in material, size, length, diameter, and thus capacity. The stormwater drainage capacity for urban areas in the UK is usually designed to accept flows of either a 1-in-10 or 1-in-30-year return period (Zoppou, 2001; Ochoa-Rodríguez, 2013; Butler et al., 2018; Environment Agency, 2018). Therefore, a storm event of a greater magnitude than the system design capacity will often result in surcharge and excess runoff (Mark et al., 2004; Djordjević et al., 2005; Houston et al., 2011; Ochoa-Rodríguez, 2013; Guerreiro et al., 2017; Leitão et al., 2017; Dawson et al., 2020). In many cases, the capacity of a system is reduced due to operational malfunctions such as blockages, ageing infrastructure and lack of capacity in pipes, particularly in extreme rainfall events (Schmitt et al., 2004; Palla et al., 2018).

Although the challenges associated with representing drainage capacity are known, the effective capacity of these systems is still misrepresented in models used for flood risk management (Palla et al., 2018; Ferguson and Fenner, 2020). Flood models (e.g., built using Flood Modeller Pro, TUFLOW or HEC-RAS etc.) are used to assess the rainfall response of a catchment and are used to answer questions about where and when flooding will occur. These models are therefore key tools in the planning and implementation of flood-mitigating interventions (Teng et al., 2017; Rehman et al., 2019). While natural characteristics of catchments such as elevation, land use and rainfall are represented explicitly, the capacity and performance of the systems are often assumed and/or oversimplified. (Chang et al., 2015; Yu et al., 2016; Palla et al., 2018; Singh et al., 2021b).

The key elements driving the oversimplification of drainage networks in flood models are the lack of data availability, complexities associated with drainage network modelling, and shortage of skill required for drainage network modelling (Fenner, 2000; Freni et al., 2009; Yu et al., 2016; Vercruysse et al., 2019). Of these elements, data availability has been a particular challenge for the study of drainage systems and flood modelling, as explicit drainage network data can be commercially sensitive and extensive to model explicitly.

The most common method of drainage capacity representation in flood modelling is using a rainfall removal rate, where a constant rate of rainfall is subtracted from that falling from the sky, with the assumption that this is handled by the drainage system and therefore does not need to be explicitly included in the overland flood model (Chang et al., 2015; Wang et al., 2018). The rainfall reduction approach was also applied to produce the national Risk of Surface Water Flooding (RoSWF) map for England and Wales (Environment Agency, 2013; Chang et al., 2015; Ferguson and Fenner, 2020). Wang et al (2018) and Chen et al (2009) also implemented the national average removal rates

(NARR) and applied a fixed reduction of 12 mm/hr to the design rainfall to represent the function of the stormwater systems. Vercruysse et al (2019) applied a drainage capacity estimate when modelling a 1-in-50-year flood event for Newcastle-upon-Tyne and produced flood risk maps that identified source areas that contributed significantly to flood hazards in an urban domain. Assuming and estimating the capacity of drainage systems in pluvial flood modelling consequentially leads to the oversimplification of the source of the hazard itself such as blockage in gullies and inlets or surcharging manholes (Maksimović, 2009; Walsh et al., 2012; ten Veldhuis et al., 2015).

Other methods of estimating drainage capacity include the use of surcharge hydrographs at manholes, however, this assumes water can only move from the sewer system to the surface (Hsu et al., 2000). More technical approaches, such as combining sewer flow models with overland flow models (flow of water over the land surface in two dimensions) have also been used (Adeogun et al., 2015; Teng et al., 2017; Martins et al., 2018). However, these models are computationally demanding, and require information regarding the network. Lastly, generating synthetic drains to include in the models has also been explored, however, this faces significant challenges associated with validating large-scale synthetic drainage models (Möderl et al., 2009; Bertsch et al., 2017).

The Drainage Wastewater Management Plans (DWMP) enable water companies to work together and improve the robustness of drainage infrastructure for its customers and the environment. The DWMP also addresses requirements associated with improving transparency and long term resilience outlined in the UK government's Strategic Policy Statement (Defra, 2017; Ofwat, 2017; Water UK, 2019; Jenkins, 2020) One of the key tools developed as part of the DWMP to improve transparency and long-term planning is the capacity assessment framework (CAF). The CAF is a tool that provides information on the capacity of the drainage system. The outputs from this framework show the change in available capacity within the drainage system over time.

This paper utilises the outputs generated by the newly available CAF to represent drainage systems more explicitly in flood models. (Water UK, 2019). Specifically, the goal is to gain insight into the value of using spatially varied drainage losses and to investigate if this makes a difference in the modelling results. Achieving this goal aids in demonstrating a methodology for using the CAF data outputs for drainage representation and evaluate the impact of this data in comparison with the existing method of drainage representation (e.g., NARR). This paper is the first-ever comparison and evaluation of drainage representation and subsequent flood risk using this sector-provided data. To achieve this, flood models of three flood-prone catchments in Leeds are used to develop and demonstrate the method of using the CAF outputs to evaluate the subsequent impact on flood hazard.

5.2 Data and Methods

5.2.1 Study Areas

Flood modelling was conducted for three catchments within Leeds, these are Holbeck, Wyke Beck and Lin Dyke shown in the map in **Figure 5-1**. The Holbeck catchment in the southwest of Leeds covers an area of 62.56 km^2 (**Figure 5-1**). The upstream end of the catchment is mostly rural, comprising mainly arable land, whereas the downstream reaches of the catchment are heavily urbanised consisting of residential areas, industrial buildings, and major transport links. In total, green space comprises 68% of the catchment and grey areas such as buildings, paved and unpaved roads make up 28% of the area. Flood risk in the Holbeck catchment is a combination of fluvial and pluvial flooding. Fluvial flooding is caused due to exceeded capacity in rivers. Pluvial flooding is surface water flooding caused by high-intensity rainfall in urban areas, this can be a result of artificial drainage systems capacity being exceeded. Wyke Beck covers 38.87 km^2 of Leeds, 63.13% of the catchment is made up of buildings, paved and unpaved roads, whereas 36.87% is composed of green spaces such as parks and gardens. Wyke Beck is predominantly a residential catchment, with a significant number of businesses. Flooding within the catchment is a combination of fluvial and pluvial mechanisms. The total area of Lin Dyke is 22.91 km^2 and has two main urban towns, Garforth located upstream, and Kippax located midstream. The downstream area of the catchment is mostly wetland, which drains into the river Aire. Green space makes up 78% of the catchment and grey areas cover 22% of the catchment. Flooding within the catchment is primarily pluvial.

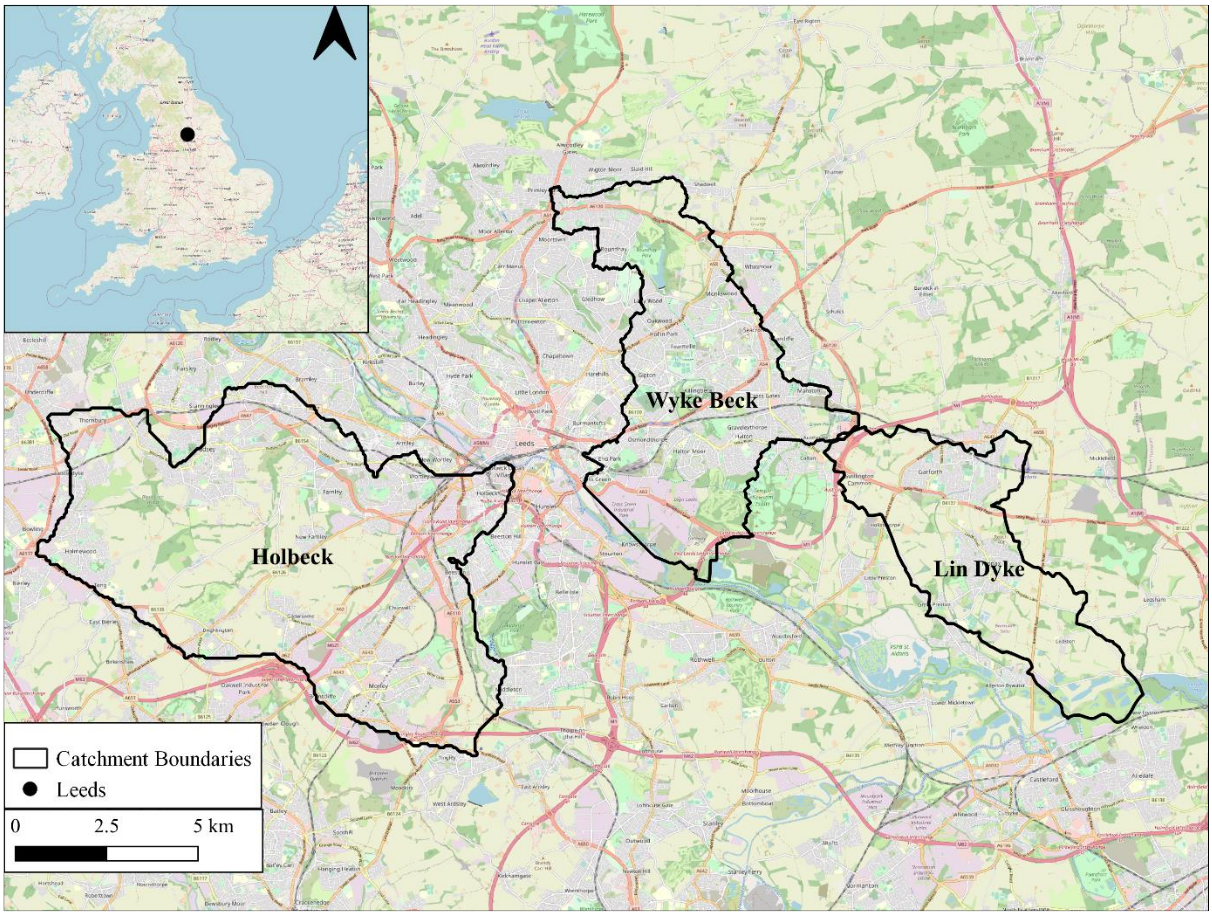

Figure 5-1: Three study area catchments located in Leeds, north of England in the United Kingdom

5.2.2 Capacity Assessment Framework Data

The outputs of CAF used in this paper were derived from water companies detailed hydraulic modelling of the combined drainage networks. Key inputs of drainage models used to generate the CAF outputs are network data and ancillary structures specified in **Table 5-1** (Gorton et al., 2017b; Gorton et al., 2017a; Udale-clarke, 2018; Water UK, 2019). The outputs are presented by assigning a score for the capacity of the network system (explained in Section 2.3).

The CAF data provided by Yorkshire Water were in GIS shapefile format and processed using QGIS. A set of capacity hexagons clipped for the study areas is presented in **Figure 5-2**. Each hexagon has a diameter of 0.5 km^2 and a score of 0 to 5, where 0 represents no data and scores of 1 to 5 represent the percentage length of pipes in that hexagon that are likely to surcharge in (Table 2). The CAF data set provides the hexagon score, the total length of pipes modelled per hexagon and the total length of pipes that will exceed capacity for a specified return period (also known as red-length).

To assign an aggregate score to each hexagon first, the scoring of drainage system performance is assessed by establishing a capacity metric for pipes and CSOs individually. Individual scoring is identified using the surcharge return period for pipes, the average number of spills per year for CSOs and the average number of spills per summer for CSOs. Additional factors used to generate the individual scores are specified in Table 1S ('S' denotes supplementary material). Using this information, an aggregate score is assigned to each hexagon by calculating the percent length of individual pipes classified as red pipes per hexagon. Red pipes are defined as pipes that surcharge in a given storm event. There are three methods in which aggregate scores can be calculated and applied for pipes and CSOs. These are:

$$Length\ of\ pipe = \frac{Total\ Length\ of\ pipes\ with\ a\ RED\ individual\ score\ x\ 100}{Total\ Length\ of\ all\ pipes}$$

Equation 15

$$Population\ equivalent = \frac{Population\ equivalent\ upstream\ of\ all\ red\ pipes\ x\ 100}{population\ equivalent\ upstream\ of\ all\ pipes.}$$

Equation 16

$$CSO\ Scoring = \frac{Total\ number\ of\ points\ scored\ by\ CSO\ x\ 100}{Total\ number\ of\ CSOs\ x\ 2}$$

Equation 17

Table 5-1: Key urban drainage components used to derive the CAF outputs.

Input Category	**Description**
Network Data	• Manhole locations, cover levels and chamber floor levels • Pipe locations, dimensions, and invert levels • Network connectivity such as gradient, bifurcation
Ancillary structures	• Combined Sewer Overflows (CSOs) • Pumping stations • Wastewater treatment works • Storage tanks • Control structures (including weirs, sluice gates, orifices, flap valves, outfalls etc.)

Table 5-2: Hexagon score and % length of pipes likely to surcharge for a specified return period

Risk Score	**Percentage length of pipes flooding**
0	No data
1	0-15
2	15-30

3	30-45
4	45-60
5	60-100

The CAF outputs include representation of drivers that affect drainage network performance. Parameters that affect system performance and capacity are population change, decrease of permeability in urban areas due to increase in urbanisation, and climate change.

5.2.3 Flood Modelling

HEC-RAS 6.1 was used for modelling flooding in each of our catchments. The inputs used for the modelling (Table 3) were a digital elevation model (DEM), land use and net hyetograph after the removal of representative losses due to the physical characteristics of the catchment (infiltration, evapotranspiration etc.)

All models use a bare earth LiDAR DEM at a resolution of 2 meters for Holbeck, Wyke Beck and Lin Dyke (Environmental Agency, 2019). The DEM was adjusted to represent buildings by identifying the cells that overlapped with building vectors defined by OS Mastermaps, these building footprints were raised in elevation by 5 m to ensure that water flows around these structures, additionally, kerbs were inserted by assuming a uniform kerb height of 10 cm to realistically represent urban morphology. Design storm periods for a 1-in-10 year, 1-in-30 year and 1-in-100-year return period for each catchment were generated using the Revitalised Flood Hydrograph model (ReFH2). The ReFH2 uses the physical attributes of a catchment to estimate rainfall depth for a required frequency and duration (Kjeldsen et al., 2013; Wallingford Solutions, 2016).

Two methods were used to represent drainage losses:

1. The National Average Removal Rate (NARR) of 12 mm/hr was applied uniformly across the whole catchment.
2. The CAF outputs were used to generate unique removal rates per risk score hexagon, which we will refer to as the CAF removal rates from here on.

The CAF-based removal rate uses the method detailed in Section 2.3.1 below, the CAF data set provided was for a 1 in 30-year return period. In summary, the CAF outputs have been used to interpolate drainage loss removal rate values to create a unique hyetograph for each hexagon risk score resulting in spatially varied hyetographs applied across each catchment. The red length per risk score for a 1 in 30-year return period was averaged and utilised to provide a more realistic representation of the capacity of the drainage system within the area.

Table 5-3: Data sets used for model build for the three study areas.

Dataset	**Source**	**Format**	**Description**
DEM	Environmental Agency	Raster	LiDAR composite DTM
Catchment Boundary	UK Centre for Ecology and Hydrology	Vector	Outlines the boundary for the catchment obtained from the FEH web service
Land Use	OS Mastermap	Vector	Details of various land-use types within the study area
Rainfall Input	REFH2	CSV	Design storm profiles for various return periods.

5.2.4 Linear Interpolation of CAF data

The CAF was used to interpolate drainage removal rate values that should be applied based on the average percentage of red-length pipes per hexagon score. The national average removal rate of 12mm/hr was used as the upper threshold to ensure that the removal rate is not higher than 12mm/hr because this is the typical value for drainage removal rates across catchments in England and Wales. In areas of known low drainage capacity, Lead Local Flood Authorities (LLFAs) have been guided to substitute alternative values of 6mm/hr hence this was chosen to represent areas that have a risk score of 5 (Environment Agency, 2013).

To interpolate drainage removal rate values, the average percentage of red length per hexagon score was calculated for each study area and each risk score. The average red length of pipes per hexagon score is therefore assumed to be a relevant proxy for capacity and therefore loss removal rate, as it indicates on average the length of pipes that will have their capacity exceeded. Equation 18 was used to calculate the slope of a line (m) and Equation 19 was used to calculate the drainage removal rates (y).

$$\boldsymbol{m = \frac{(y_2 - y_1)}{(x_2 - x_1)}}$$

Equation 18

$$y = y_1 + m(x - x_1)$$

Equation 19

Where, y_1 denotes the minimum removal rate and y_2 denotes the maximum removal rate (i.e., 6 mm/hr and 12 mm/hr), x denotes the percentage of pipes at red-length x_1 is 0 i.e., the minimum % of pipes at red-length and x_2 is the maximum percentage of red-length pipes i.e., 100 %.

5.2.5 Postprocessing of model outputs

All results were processed to analyse the hazard measures i.e., depth, velocity and extent posed by the scenario that uses the NARR and the scenario that uses CAF removal rates within each catchment. To identify the flooded area, all cells with a water depth greater than 0.1 meter and velocity greater than 0.25 m/s were used. The flood hazard maps were further processed to assess the U.K. Hazard Rating, as recommended in the flood risks to people guidance using Equation 20 (DEFRA, 2006; Hunt, 2009).

$$Hazard = D * (V+0.5) + DF$$

Equation 20

where, *D* = depth (m), *V* = velocity (m/s) and *DF* = debris factor. Where the debris factor is either 0, 0.5 or 1 depending on the depth, velocity, and land use. The most recent guidance states to use a depth-varying debris factor with a non-zero value at low flood depths. The depth and velocity used to calculate the flood hazard rating as per the U.K. Hazard Rating are presented in **Table 5-4**.

Table 5-4: Depth and velocity classifications for the UK hazard ratings (Defra, 2006; Hunt 2009)

Hazard	Rating	Depth (m)	Velocity (m/s)	Description
Low	< 0.75	0.1 – 0.3	< 0.25	Considered safe, depth is likely to exceed the height of the kerb. Velocity is that of still waters.
Moderate	0.75 – 1.25	0.3 – 0.6	0.25 – 0.5	Hazard to some such as children and elderly, likely to cause some property flooding and damage to vehicles
Significant	1.25 – 2.0	0.6 – 1.2	0.5 – 2.0	Hazard and danger to most, unsafe for vehicles, most likely to cause property damage and breach flood resilience measures
Extreme	>2	> 1.2	> 2	Unsafe for all including emergency services, likely to cause building failure

Lastly, any figures with a suffix of 'S' have been presented in the supplementary material.

5.3 Results

5.3.1 CAF Scores

To generate the hyetograph inputs for rainfall-runoff modelling for each of the study areas, the average length of red-length pipes per risk score was calculated. **Table 5-5** presents the average length of red length pipes for the whole of each catchment modelled. The ratio of red-length pipes to total pipes modelled per risk score is presented in **Figure 5-2**. For all three catchments, the ratio of total pipes modelled and the average % of red-length pipes increase as the risk score increases. This means that although the length of pipes for hexagons that are classified as a risk score of five is small, most of the length of those pipes will surcharge in a 1-in-30-year return period event. This trend is observed across the three catchments as seen in **Figure 5-2**, where all three catchments have values over 70% for the average percent length of red-length pipes. This trend is reversed for pipes modelled under hexagons classified as a risk score of 1, where the average percentage of red-length pipes is below 10% for each of the catchments. Overall, 12.45% of the total pipes in the Holbeck catchment are red-length pipes. In Wyke Beck, 14.91% of the total pipes modelled are red-length, and for the catchment of Lin Dyke 21.80% of the pipes modelled are red-length.

Table 5-5: Average length of red-length pipes per risk score for each catchment

	The average length of red-length pipes per catchment (km)		
Risk Score	**Holbeck**	**Wyke Beck**	**Lin Dyke**
1	5.78	6.65	4.24
2	22.08	20.17	20.19
3	35.27	32.50	36.60
4	49.48	52.30	49.07
5	71.33	87.04	81.61

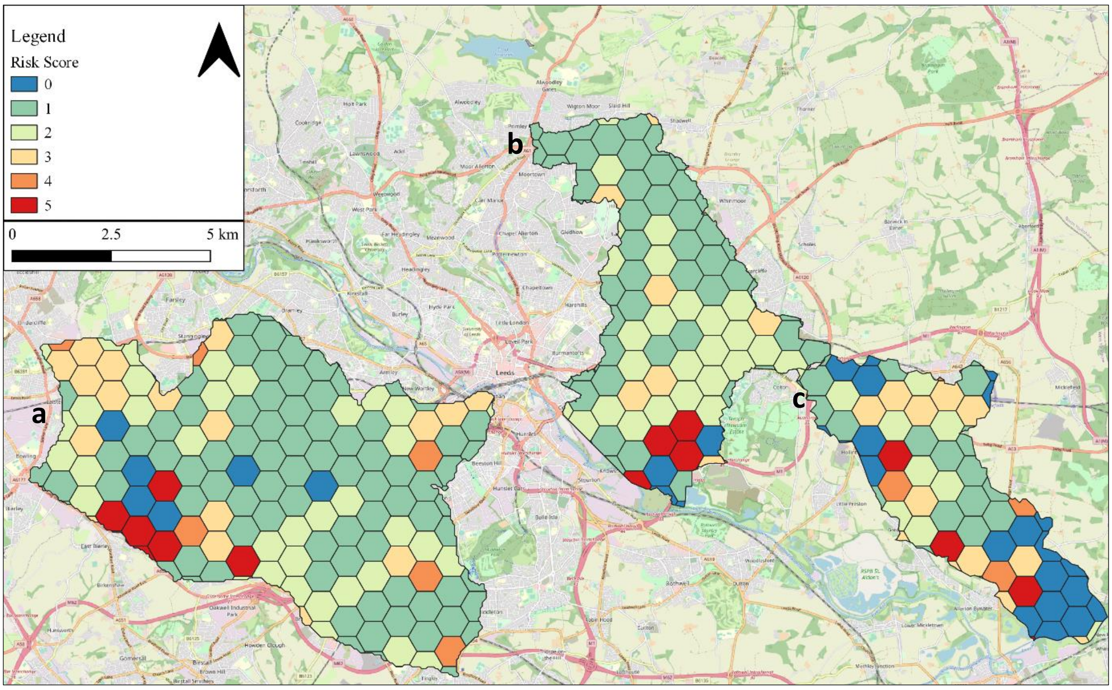

Figure 5-2: The CAF outputs showing the capacity i.e., percent of pipes likely to flood based on the hexagon risk score for a) Holbeck b) Wyke Beck and c) Lin Dyke

The total length of pipes modelled is 3,410,905 km, 1,906,096, km, and 931,128 km, for the Holbeck, Wyke Beck and Lin Dyke catchment respectively. The total length of pipes at red length is

423,606.94 km, 284,229.91 km, and 203,026.40 km, for the Holbeck, Wyke Beck and Lin Dyke catchment, respectively. Red length pipes, irrespective of score make up 12.41 %, 14.91 % and 21.80 % of total length of pipes modelled within the Holbeck, Wyke Beck and Lin Dyke catchment. The total length of pipes modelled for hexagons that score one is considerably higher for each catchment. For example, 26.27%, 32.01 and 22.05% for Holbeck, Wyke Beck and Lin Dyke when compared to the total length modelled for hexagons that score 5, i.e., 4.33%, 1.63% and 11.46% for each of the catchment respectively (**Table 5-6**, and Figure 1S).

Table 5-6: Percent of red length pipes and percent of total pipes modelled per risk score and per catchment.

	Total length of red length per score risk score (%)			**Total length of pipes modelled (%)**		
Score	Holbeck	Holbeck	Lin Dyke	Holbeck	Wyke Beck	Lin Dyke
1	1.54	14.49	20.78	26.27	32.015	22.05
2	15.883	14.17	21.55	23.23	32.25	23.45
3	16.43	14.33	22.25	23.86	32.46	21.58
4	16.31	31.41	21.664	22.28	1.62	21.43
5	17.65	32.73	23.68	4.33	1.63	11.46

5.3.2 Rainfall Inputs

Based on the average percent of red-length pipes per risk score for each catchment, a drainage removal rate was interpolated to estimate the capacity of pipes **(Table 5-7)**. The newly calculated capacity estimates were used instead of the 12mm/hr national average. The drainage removal rates were calculated using the methodology outlined in Section 2.3.1 and have been presented in Table 5 for each catchment. These values were then utilised to generate a unique net-hyetograph for each hexagon, for the return periods of 1-in-10-year, 1-in-30-year, and 1-in-100-year per catchment (**Figure 5-3**). For any hexagons that score a zero, i.e., no data available, the default NARR of 12 mm/hr has been used.

Table 5-7: Peak drainage removal rate (mm/hr) for each study area and related hexagon risk score.

CAF Risk Score	**Holbeck**	**Wyke Beck**	**Lin Dyke**
No Data	12	12	12
1	11.65	11.60	11.74
2	10.67	10.78	10.78
3	9.88	10.04	9.80
4	9.03	8.86	9.05
5	7.72	6.77	7.10

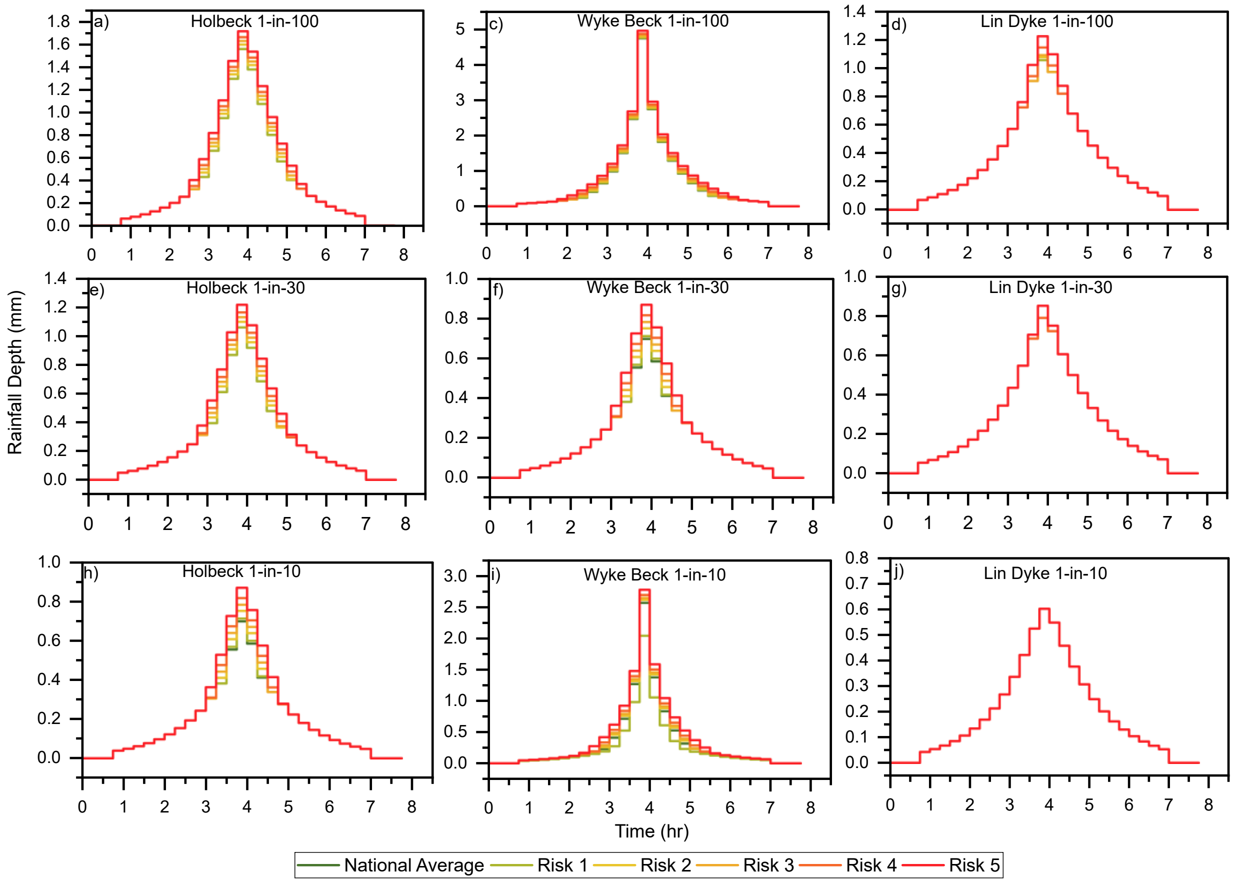

Figure 5-3: Net-hyetograph inputs for Holbeck (a, e, h), Wyke Beck (c, f, i) and Lin Dyke (d, g, j) for a 1-in-10-year, 1-in-30-year, and 1-in-100-year return period.

Common between the net-hyetographs of all the catchments is the increase in peak net-rainfall and total net-rainfall when using the CAF-derived removal rates for the return periods of 1-in-30-year and 1-in-100-year. When compared to the peak net-rainfall of the NARR, net-peak rainfall in the Holbeck catchment increases by 24.51%, 10.06% and 14.84%, for the return periods of 1-in-10-year, 1-in-30-year and 1-in-100-year, respectively. Similarly, for Wyke Beck, the increase is 8.01%, 4.45% and 6.09%, for the return periods of 1-in-10-year, 1-in-30-year and 1-in-100-year.

The catchment of Lin Dyke, however, only experiences an increase in peak and total net-rainfall for the return periods of 1-in-30-year and 1-in-100-year. The net-hyetographs for the 1-in-10-year event, have no difference when compared to that of the NARR. Additionally, Holbeck and Wyke Beck have a unique net-hyetograph for each hexagon score for each return period, however, Lin Dyke only has a unique hyetograph for each risk score for a 1-in-100-year return period. Furthermore, the hyetographs for a 1-in-30-year return period, are only different for hexagons that are classified as a risk score of five.

Other differences are observed in the hyetographs of the Holbeck catchment which demonstrates the greatest difference in rainfall depth values when approaching the peak, however, for Wyke Beck, a more pronounced difference between the hyetographs for each risk score is observed in the rising and falling limbs of the hyetographs. **Figure 5-4** shows the percent difference in total rainfall when compared to the total net-rainfall of the NARR.

Holbeck and Wyke Beck show the greatest difference in the rainfall totals for each risk score when compared to the NARR net-rainfall total. Both Holbeck and Wyke Beck also show that the difference in net- rainfall total decreases as return period increases, for instance, the difference between NARR and CAF removal rates net-rainfall totals for Holbeck decreases from 17.38% to 14.14% for risk score five hexagons from the return periods of 1-in-10-year, 1-in-30-year, 1-in-100-year. Similarly, for Wyke Beck the difference in net-rainfall totals when compared to NARR decreased from 21.66 % to 15.89%. Like the net-hyetographs, Lin Dyke has no difference in the rainfall totals for a 1-in-10-year event. A small difference of 0.23% and 2.31% is observed for hexagons that score four and five for the 1-in-30-year return period when compared to the totals of the NARR. The 1-in-100-year return period shows a difference in the net-rainfall totals for risk score three to five. The net-rainfall totals increase by 0.35%, 2.79%, and 7.58%, respectively, when compared to the totals of NARR.

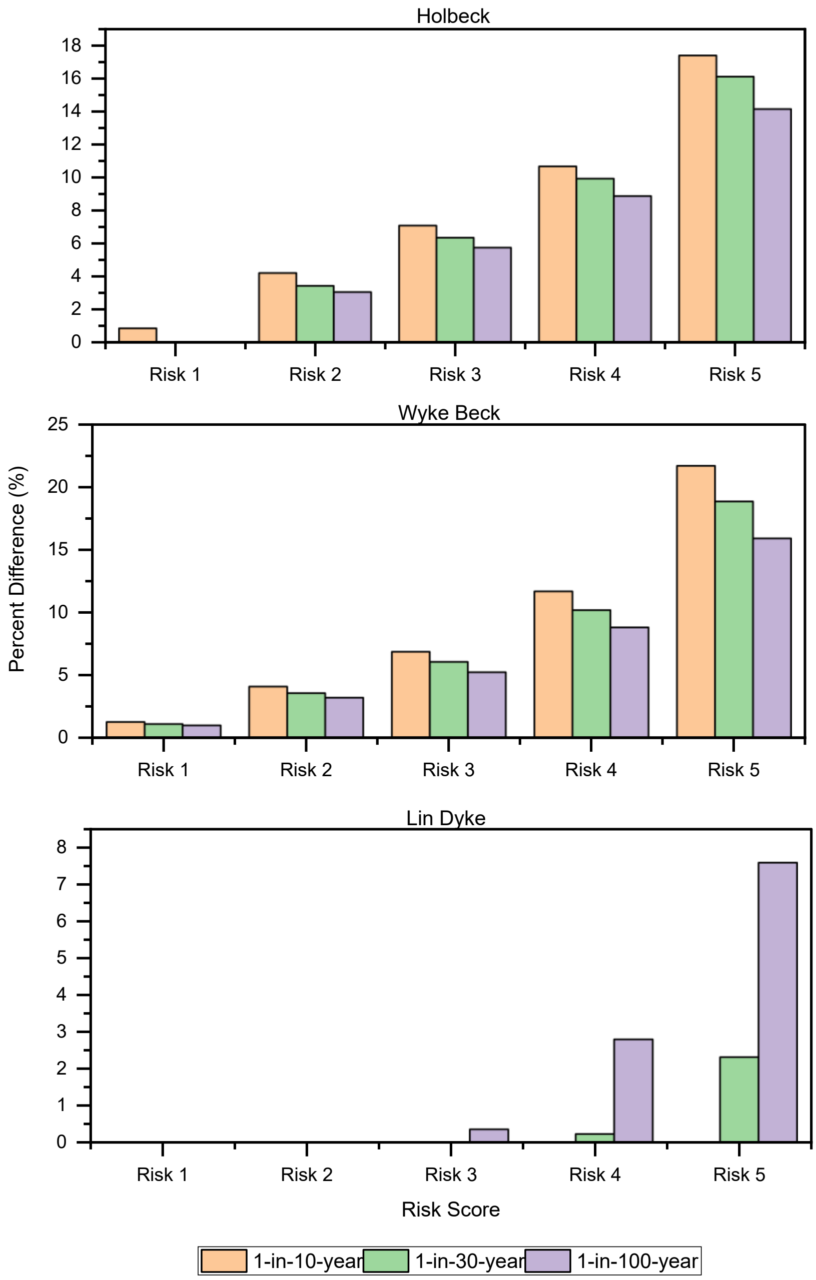

Figure 5-4: Difference in net-rainfall totals when compared to the net-rainfall total of the NARR scenario for all return periods for the catchments of (a) Holbeck (b) Wyke Beck (c) Lin Dyke

5.3.3 Flood Modelling

For all catchments, CAF-derived outputs generate an increase in flood depths and velocities. The total area of each catchment flooded for the three return periods and the two drainage removal rates scenarios (i.e., CAF vs NARR) are presented in **Table 5-8**. The total area of the Holbeck catchment that is flooded when using the NARR is 6.17 km^2, 6.80 km^2, and 7.56 km^2 for the return periods 1-in-10-year to 1-in-100 years, respectively. When using the CAF-derived removal rates, this total area flooded is increased to 6.24 km^2, 6.85 km^2, and 7.61 km^2. When compared to the flooded area predicted by the NARR, the CAF removal rates results increase the flooded area by, 1.11%, 0.79% and 0.61%, for 1-in-10-year, 1-in-30-year and 1-in-100-year return periods. Similarly, for the Wyke Beck catchment, the difference in total area flooded area is less than 1% when comparing the NARR and CAF removal rates for all return periods. The total flooded area for the Lin Dyke catchment for a 1-in-10-year and a 1-in-30-year return period shows no difference between NARR and the CAF removal rates scenarios. However, for a 1-in-100-year return period, there is an 8.36 % difference in the total area flooded within the Lin Dyke catchment. The total area flooded when using the NARR is 10.75 km^2, this increases to 11.65 km^2 when using the CAF removal rates. Additionally, this increase of 12.05% and 4.52% due to the CAF removal rates is mostly observed at shallow depths of 0 to 0.15m and 0.15m to 0.30m.

Like the depth ranges, the results for the velocity ranges also indicate small differences between the two drainage removal rate scenarios for all return periods. Most of the flooded area within the Holbeck catchment for each of the return periods is exposed to a velocity of 0 to 0.25 m/s which is considered safe for all. All differences in velocities between the NARR results and CAF removal rates results are no greater than 1.12% for the Holbeck catchment, with the maximum difference observed for a 1-in-10-year return period. Similarly, the velocities within the flooded area for Wyke Beck remain similar between the two scenarios where the differences in the results are less than 1%. The velocity results for Lin Dyke show that there is a difference in velocity ranges experienced by the total flooded area for a 1-in-100-year return period. The largest difference between the NARR and the CAF removal rates is observed at the velocity range of 0.25 m/s to 0.50 m/s. The CAF removal rates predict a 26.56% increase in the total flooded area exposed to this velocity range when compared to the NARR. This velocity range is expected to be dangerous for the elderly and children and causes damage to vehicles and some property flooding. Furthermore, there is a 7.45% increase in areas subjected to 0 to 0.25 m/s velocity.

The results for the hazard rating classifications show a greater percentage difference when comparing the NARR and CAF removal rates scenarios. The Holbeck catchment shows a 3.75 %, 2.43% and 1.07 % increase in overall hazard rating for a 1-in-10-year to 1-in-100-year return period. Moreover, moderate, and significant hazards when using the CAF removal rates are increased by 9.04 % and 7.21 % for a 1-in-10-year return period. For a 1-in-30-year and 1-in-100-year return period, the CAF removal rates predict a 1.78 % and 1.34 % increase in moderate hazard. Unlike Holbeck, Wyke Beck shows the greatest difference in hazard ratings for a 1-in-30-year return period when comparing the NARR and CAF removal rates. Moderate hazard is increased by 13.52 % and significant hazard is increased by 6.99 %. There is no difference in the hazard results for a 1-in-10-year event for the Lin Dyke catchment when comparing the NARR and CAF removal rates. Furthermore, the 1-in-30-year predicts less than a 1 % increase in overall risk within the two scenarios. However, for a 1-in-100-year event, the CAF removal rates predict a 15.29% increase in low hazard, but an 11.80% decrease in moderate hazard. This pattern of change matches that of the depth results for Lin Dyke where the CAF removal rates increase shallow flooding.

Table 5-8: Total flooded area and hazard extent for each catchment, across the three return periods and flood modelling scenarios that use the NARR and CAF removal rates.

	1-in-10-year					
Catchment	**Holbeck**		**Wyke Beck**		**Lin Dyke**	
Removal Rate scenario	**Total Flooded Area** (km^2)	**Hazard extent** (km^2)	**Total Flooded Area** (km^2)	**Hazard extent (km^2)**	**Total Flooded Area** (km^2)	**Hazard extent** (km^2)
NARR	6.17	1.31	5.02	1.21	9.70	1.58
CAF removal rates	6.24	1.36	5.06	1.26	9.70	1.58
Difference	0.07	0.06	0.04	0.05	0	0
	1-in-30-year					
NARR	6.80	1.80	5.55	1.62	9.86	2.11
CAF removal rates	6.85	1.85	5.59	1.65	9.86	2.12
Difference	0.05	0.05	0.04	0.03	0	0.01
	1-in-100-year					
NARR	7.56	2.45	6.17	2.08	10.75	2.78
CAF removal rates	7.61	2.48	6.21	2.12	11.65	2.86
Difference	0.05	0.04	0.04	0.04	0.10	0.08

Figure 5-5 marks the four key locations in which the difference between the NARR and CAF removal rates can be observed for the hazard ratings of a 1-in-100-year event. All the key locations are situated in the two urban areas of Lin Dyke, Location 1(**Figure 5-6**, Figure 2S) and Location 2 (Figure 2S and Figure 5S) located in Garforth showing how the hazard rating has increased between the two scenarios. For instance, Location 1 shows a 100% increase in the extent that is a classified extreme hazard when using the CAF removal rates for drainage representation. Moreover, the significant

hazard is increased by 21.37%, and low and moderate hazards have decreased by 7.92 % and 6.80 %, respectively at Location 1 when compared to the NARR hazard outputs. Additionally, Location 2 indicates a decrease in low, significant, and extreme hazards, however, moderate hazards at the location increase by 10.12% when using the CAF removal rates. In Location 3 (Figure 3S, Figure 6S) moderate, significant, and extreme hazard has increased by 9.54%, 17.05% and 11.68%. Extreme hazard increase by 100% in Location 3 when using the CAF removal rates scenario. Location 4 (Figure **5-7**, Figure 7S) shows that when using the CAF removal rates, low hazard decreased by 6.43% however, moderate and significant hazard increased by 23.97 %, and 5.05 %.

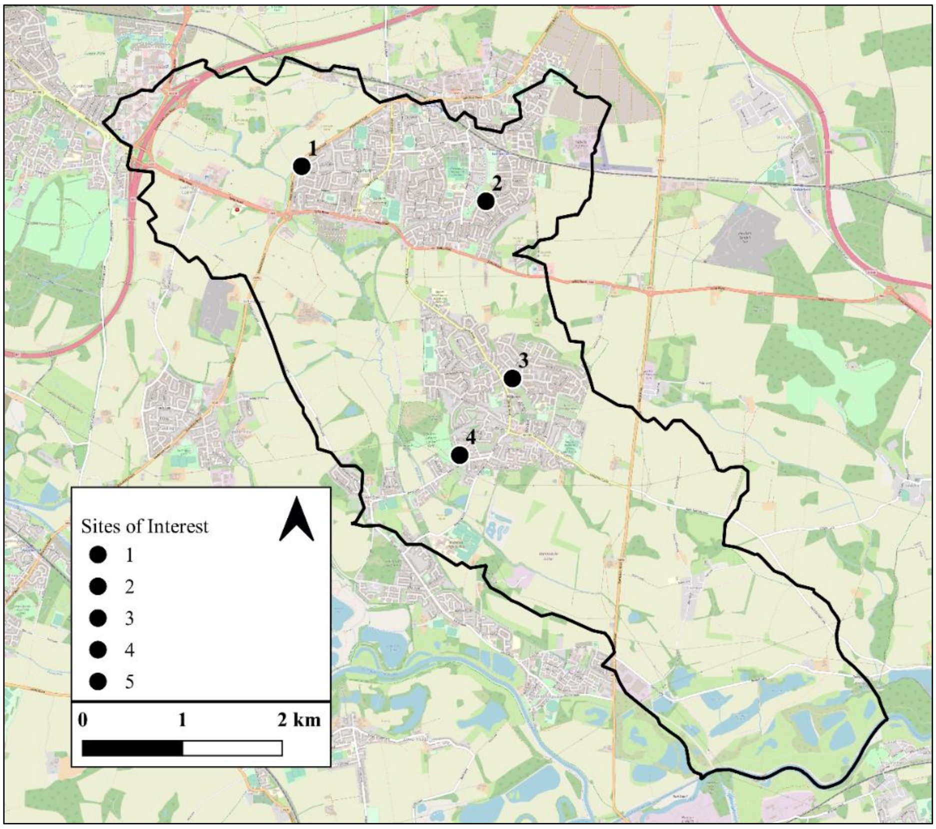

Figure 5-5: Key locations in the catchment of Lin Dyke where the difference in flood hazard category can be identified between NARR and CAF removal rates scenario for a 1-in-100-year return period.

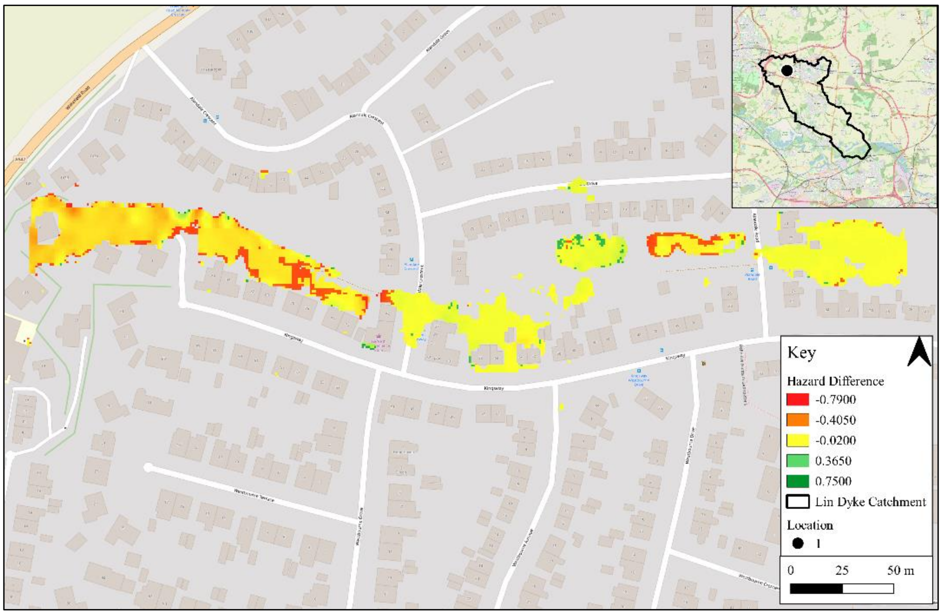

Figure 5-6: Location 1 of 4 in Lin Dyke showing the difference in the extent of hazard rating between the NARR and CAF removal rates (i.e., NARR-CAF) scenarios.

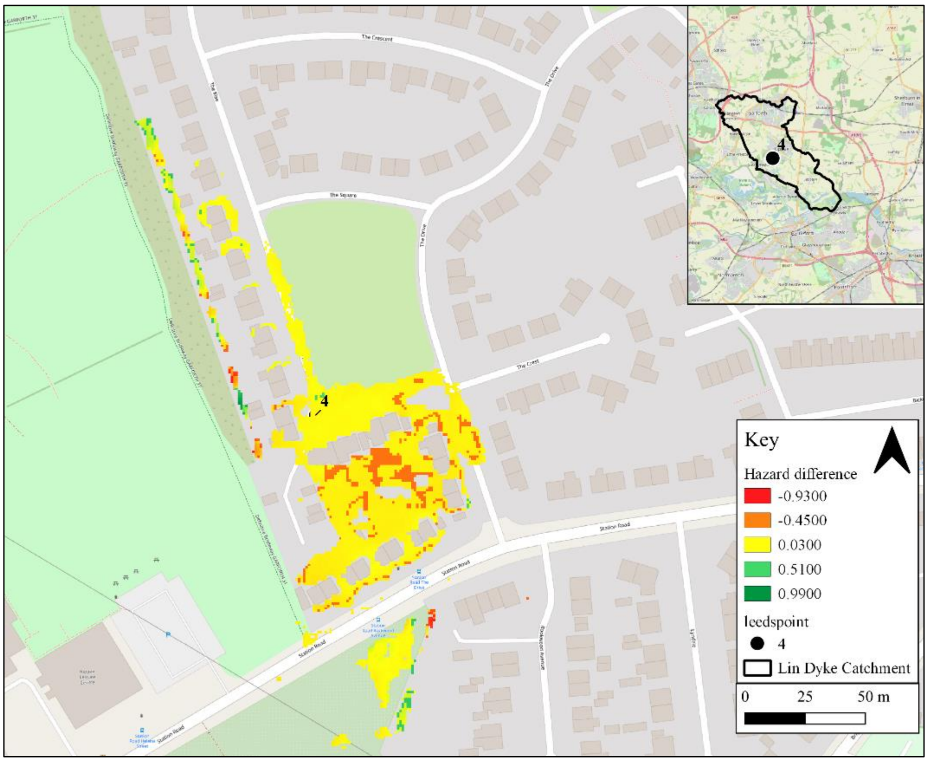

Figure 5-7: Location 4 of 4 in Lin Dyke showing the difference in the extent of hazard rating between the NARR and CAF removal rates scenarios.

5.4 Discussion

The results indicated that the CAF outputs when used to estimate drainage capacity make a tangible difference to the net-hyetographs used as inputs into the models for each catchment. These differences are in the range of 0 to 24 % for the Holbeck catchment, 0 to 8 % for the Wyke Beck catchment and 0 to 8 % for the catchment of Lin Dyke. Although there are significant differences in the rainfall inputs, this difference, does not always translate to a major flood risk increase. Based on the results, using the CAF-derived drainage removal rates results in less than a 2 % increase in flood risk overall within the Holbeck and Wyke Beck catchment when compared to outputs generated using the NARR of 12 mm/hr. These differences are consistent across flood depths, velocity, hazard and return periods.

The simulated results for the Lin Dyke catchment, however, show a larger variation in flood risk when comparing the NARR and CAF removal rates results. The results indicate that although there is minimal difference between the outputs for the 1-in-10-year and 1-in-30-year events, there is a larger difference of 8.36 % in the outputs of the 1-in-100-year event. The results indicate that the CAF-derived inputs increased the catchment area exposed to shallow flooding, but decreased the area exposed to deeper flooding. Locations 1 to 4 present where the differences in flood extent and hazard pose a significant risk to properties. On a large scale an 8.36% difference in flood extent may seem small, this difference is important at a local scale for stakeholders concerned with funding flood defences, housing, and any future infrastructure projects.

When using the CAF removal rates scenarios as inputs, volume of rainfall received by each catchment was increased. However, this increase in rainfall inputs did not translate to an increase in overall flood risk within the catchments, indicating a non-linear system that is governed by thresholds. Even though the difference is generally small, the CAF removal rates produce a slightly larger flood extent in all three case studies. The results also show that the value in the use of the CAF for drainage representation in models will vary based on the catchment itself and the local parameters. For instance, smaller catchments such as Lin Dyke may be more reactive to changes in rainfall. The open channel watercourse in the town of Garforth located in the north of Lin Dyke has been culverted in a piecemeal fashion and new drainage infrastructure has been connected, seemingly without regard to capacity limitations. Since the drainage system is already a problem, Lin Dyke is more susceptible to changes in the inputs. Furthermore, even though the drainage system hasn't been explicitly represented, any representation of the system draws even more attention to the fundamental issue. Additionally, larger storm events in large catchments likely overwhelm the catchment, i.e., once flooding has passed the out-of-bank threshold and has filled the floodplain, the increase in rainfall only marginally increases the flood extent.

Each catchment contains less than 5 percent of the hexagons that are classified as a risk score of five, this likely has a small influence on the overall flood risk. Especially if these hexagons are in rural areas, or where the pipes are not directly or closely linked to the larger systems or hydraulic structures. The CAF data presented in this paper also provides an incomplete picture of the sewer capacity and performance of the drainage system, this is highlighted by the hexagons identified as no data. Despite that, significant areas in each of the catchments have complete data sets, therefore the data presented can still be used to design interventions at a high level. For instance, CAF data can aid in the analysis of potential estimation of the impact of increasing sustainable urban drainage systems (SUDs) in hexagons that have high-risk levels and estimate the costs and benefits of increasing green space in selected hexagons. It must be noted that the interpolation method used to derive CAF removal rates uses 12 mm/hr (as the upper threshold), and this was based on the NARR. However, different catchments will have different NARRs, as specified by the RoSWF (Environment Agency, 2013). Hence potentially, catchments that have higher NARR will show greater differences. Nonetheless, the interpolation method used to derive the CAF removal rates for the CAF risk scores is adaptable and can be amended to any given threshold, thus making it applicable to any location.

The subject of the absence of sewer modelling data however is not limited to this paper, to date, only 25% of the surface water sewers in England and Wales have been modelled. For Yorkshire, the total percentage of surface water sewers currently modelled is only 30% (Udale-clarke, 2018). Therefore, an obvious effort needs to be made to improve the coverage of models to generate complete CAF datasets. It is also important to note that some pipes are designed to surcharge significantly (without causing flooding), and the CAF does not omit these pipes from the red-length modelled, therefore some hexagons identified as high-moderate to high risk may be at a lower risk level. Additionally, it is unknown if the risk in a specified hexagon is due to the foul, combined or storm drainage system. Hence, when applying engineering interventions, it is important to consider the unknowns and uncertainty associated with the CAF inputs and outputs.

The method presented in this paper was also created to reflect current practice, so that it is easier to adopt and implement. Therefore we use REFH2 to adjust the hydrographs to allow for drainage capacity based on the risk score and the interpolated values. Hence, the expertise required for this method is similar to the expertise that would be required for a normal modelling study with no significant additional budget being required to implement the methodology (Petrucci and Tassin, 2015; Teng et al., 2017). Although the removal rates for NARR and CAF have been compared, a detailed uncertainty analysis has not been done. Uncertainties also include characteristics such as varying rates of urbanisation, lack of model validation and rainfall variability and therefore should be considered for any further work associated with using the NARR and the CAF.

The results presented in this paper do not include the impacts of climate change on the rainfall inputs or a future increase in population, however, the CAF datasets do include these in aggregate scores for the epoch of 2030, 2050 and 2080. Under future scenarios, the capacity and performance of drainage systems are likely to deteriorate. Moreover, the frequency of extreme events is projected to increase, the Environment Agency guidance for rainfall uplifts for the region of Leeds is 20% central allowance and 35% upper-end allowance for the epoch 2050. For epoch 2070 the uplift allowance changes to 25% for the central allowance and 40% for the upper-end allowance (Met Office Hadley Center, 2019). The combination of ageing infrastructure with an increase in extreme events suggests that a better representation of real drainage systems capacities is becoming more important and will make local solutions more resilient and relevant to the realities on the ground.

5.5 Conclusions

In this paper, a methodology to use the CAF outputs for the representation of spatially varied drainage capacity was successfully implemented in flood models for the first time for three catchments in Leeds. The availability of the CAF data provides insights into the current state of the drainage system within catchments in the form of red-length pipes and aggregate scores. Using the information provided by the CAF dataset, a novel approach is developed to translate CAF risk scores into spatially varied drainage removal rates that can be used in flood models to better represent real drainage systems. The proposed approach improves on the simplified use of the 12 mm/hr national average drainage removal rate that is normally used to represent drainage systems uniformly across a catchment.

The developed methodology for converting CAF risk scores to drainage removal rates was applied to three urban catchments in Leeds, UK, namely, Holbeck, Wyke Beck and Lin Dyke. The three catchments have a long history of flooding and are key locations of current and future flood risk management. Three return periods and two scenarios for each return period were used to demonstrate the use of the CAF data set and the impact it has on flood risk. For two out of three catchments, flood risk only moderately increases, however, the catchment of Lin Dyke showed important local differences in the flood risk when using the CAF-derived rainfall removal rates for drainage representation.

The results show that the CAF dataset produced an increase in the rainfall inputs that are used for flood modelling, however, the increase in rainfall inputs did not always translate to an increase in flood extent. The difference in the extent and magnitude of flood risk is a function of the individual characteristics of the catchment. These characteristics include but are not limited to, urban extent, topography and the number of hexagons that have a high-risk score. Additionally, the analysis showed that the model results were not, at an average scale, largely affected by a variable representation of drainage removal rates derived using the CAF for the catchments. However, these small differences may still be of great importance when implementing flood risk management strategies, future developments, and investments.

In this case, three case studies were used which responded differently to the use of CAF-derived drainage representation. This indicates that drainage representation is valuable in flood models, however, the importance is a function of the catchment, location, and scale. Therefore, applying the CAF dataset and the methodology outlined in this study to other catchments in the UK is important to understand the wider implication of this dataset and methodology. Doing this will enables us to understand and quantify the implications of using variable drainage representation in flood models. Additionally, case studies are also necessary to determine how catchments with certain parameters are more sensitive to drainage representation. Further work should also focus on quantifying the value of using the CAF dataset and the methodology presented in this paper under climate change projection scenarios. Although the removal rates for NARR and CAF have been compared, a detailed uncertainty analysis has not been done, but would be useful in future work.

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Chapter 6 Evaluating the impact of climate change and drainage representation on the Unit Flood Response Approach

Abstract

Urban flood risk assessment is an essential tool for urban planning. Two-dimensional rain-on-grid modelling is used to investigate the impact of climate change and drainage representation using the unit flood response (UFR) approach for the catchment of Lin Dyke, Leeds. The UFR approach helps identifying flood source areas within a catchment and is a promising tool. However, the inclusion of multiple factors such as drainage infrastructure and climate change have so far not been utilised in the approach. Three scenarios (Baseline (BL), Baseline+Climate Change (BLCC), and Baseline+Climate Change+Drainage (BLCCDR)) are used to establish a hazard index and building exposure index. Geospatial analysis and statistical techniques calculate relative ranking and rank consistencies. The results show variation in the hazard index rankings across the scenarios. Subunit rankings demonstrated a shift in response to climate change and drainage capacity representation using the capacity assessment framework (CAF). The results demonstrate the importance of multifactorial assessment for effective urban flood risk management by including climate change projections and drainage representation when investigating flood source areas using the unit flood response methodology.

6.1 Introduction

Flooding within the UK threatens residential homes, businesses, and critical transport infrastructure. For example, the December 2013 and March 2014 flooding in the UK resulted in economic damages of ~£1,300 million in England and Wales. Residential properties account for 25% of this damage, followed by businesses (Fenn et al., 2016). Additionally, the 2015 to 2016 floods following the passage of Storm Desmond and Eva resulted in economic damage of £1.3 billion to £1.6 billion (Lashford et al., 2019). Prior to this, in 2012, flooding across nearly half the UK caused 1.2 billion in costs, with pluvial flooding contributing significantly to these losses (Heidrich et al., 2013; Lashford et al., 2019; Frantzeskaki et al., 2019)

Alterations to flood processes are a function of several interacting drivers, such as spatial and temporal distribution of precipitation, event intensity, and urbanisation level. Urbanisation and climate change are leading drivers of increased extreme events and flooding. The Met Office climate change projections for the UK indicate that extreme precipitation events will be amplified by 20% in the summer and up to 25% in the winter (Lowe et al., 2019; Murphy et al., 2019). Consequentially, this will increase the intensity and frequency of flooding, exacerbating societal, economic, and structural damage. The UK Committee on Climate Change estimates the average annual cost of flood damage in the UK to increase from £1.2 billion to over £12 billion per year by 2080 (Evans et al., 2006). To quantify the impact of increased precipitation and flooding due to climate change and improve the resilience of cities to the impact of extreme events, climate change projections are used as inputs into models to quantify and simulate the effect of extreme events on flood risk.

Flood risk assessments are the primary methodology for implementing flood defences and are where receptors are assessed. In recent years, several modelling methodologies have attempted to use modelling to spatially identify and prioritise flood source areas within a catchment instead of focusing on impact zones. For example, the unit flood response (UFR) approach is used to identify flood source areas within a catchment/watershed. The method is applied by dividing the study area into units of equal or unequal sizes, then omitting rainfall from these units *one at a time* to assess its impact on the flood peak or flood extent. Based on their contribution to the overall flood peaks or flooding extents, units are ranked to establish a Flood Index (FI), which reflects their importance in terms of prioritisation for flood management (Saghafian and Khosroshahi, 2005; Singh et al., 2021).

The UFR approach has been used to study the influence of land use change on identifying flood source areas for the Golestan catchment in Iran using the UFR approach (Saghafian et al., 2008). The results showed that the UFR approach identified the subcatchment furthest away from the outlet as a high priority; however, increasing green space within the subcatchment did not significantly reduce flood peaks for high return periods (Saghafian et al., 2008). Additionally, the effect of land use and land cover change was investigated by Sanyal et al. (2014) for the Konar catchment in India using the UFR. The results showed that land use and land cover changes positively affect the priority ranking of sub catchments.

Roughani et al. (2006) used the UFR approach to identify priority sub catchments and implement flood control measures within those catchments. He found implementing flood control measures in high-priority areas within the catchment's centre was the most effective. The approach was also utilised to identify which soil type contributed the most to overall flood risk within the Khanmirza catchment in Iran. Rezaei et al. (2017) report that clay-rich soils dominated high-priority ranking sub catchments. In recent years, the methodology has been applied to link source areas to impact in Newcastle-upon-Tyne. The results demonstrated that source areas changed based on pre-defined priority criteria, such as flooded green spaces and roads (Vercruysse et al., 2019).

In most applications for the UFR approach, the drainage system has been assumed unless explicitly represented. This is because, in the UK, drainage systems are commercially sensitive data;

the reasons for the unavailability of such drainage systems include a lack of documentation of the system itself (Li et al., 2023). Wenhui et al. (2023) explicitly represented the stormwater pipe network and storm losses to develop a framework to identify subcatchments where implementation of sensitive urban design (WSUD) would be optimised for the Voogee catchment, Australia. The results demonstrated that sub catchments identified as high priority were clustered upstream and midstream of the leading drainage network.

The UFR approach has been utilised to assess the impact of land use change and support decision-making processes. However, little attention has been given to exploring the combined effects of urban drainage systems, specifically in situations where detailed information about the drainage system is unavailable and the influence of climate change on identifying flood source areas using the UFR approach. Notably, only a study by Maghsood et al. (2019) has investigated the implications of climate change on flood source areas within the Talar Basin of northern Iran, utilising the UFR approach in conjunction with the General Circulation Models (GCM) from the Couple Model Intercomparison Project Phase 5 (CMIP5). This research revealed that climate change led to an increased priority ranking of several subcatchments in the area. When considering the combined effects of the drainage system and climate change, literature is limited on how source areas contribute significantly to flooding within a catchment change.

Drainage systems are critical urban infrastructure designed to collect, convey, and discharge excess rainwater to mitigate the impact of flooding. However, it is often designed to deal with a set capacity of flows or water depth; in the UK, the drainage system's capacity is estimated to be 12 mm/hr. Changes in rainfall extremes due to climate change combined with reduced capacity due to ageing infrastructure and increased urbanisation are increasing the strain imposed on the existing drainage systems. Hence, it is crucial to understand how climate change affects the drainage system's capacity and identify flood source areas using the UFR approach to improve understanding of flood risk for long-term resilience. The purpose of this paper is to apply the UFR approach in combination with climate change projections and drainage system representation for the catchment of Lin Dyke in Leeds, UK. This paper presents a novel approach by combining the UFR methodology, drainage representation using the CAF framework and climate change projections to identify FSAs.

7.2 Methods

7.2.1 Case Study

The case study area is the Lin Dyke catchment in Leeds, UK (**Figure 6-1**). The total area of Lin Dyke is 22.91 $km^{2,}$ and it has two main urban towns, Garforth, located upstream, and Kippax, located midstream. The downstream area of the catchment is mostly wetland, which drains into the River

Aire. The catchment has a history of flooding dating back to the 1980s. Additionally, the catchment is known to suffer from extensive surface water flooding. The main reason for this is because the open channel watercourse within the catchment has been culverted over and flows from new drainage infrastructure feed into this culvert, exceeding capacity limitations.

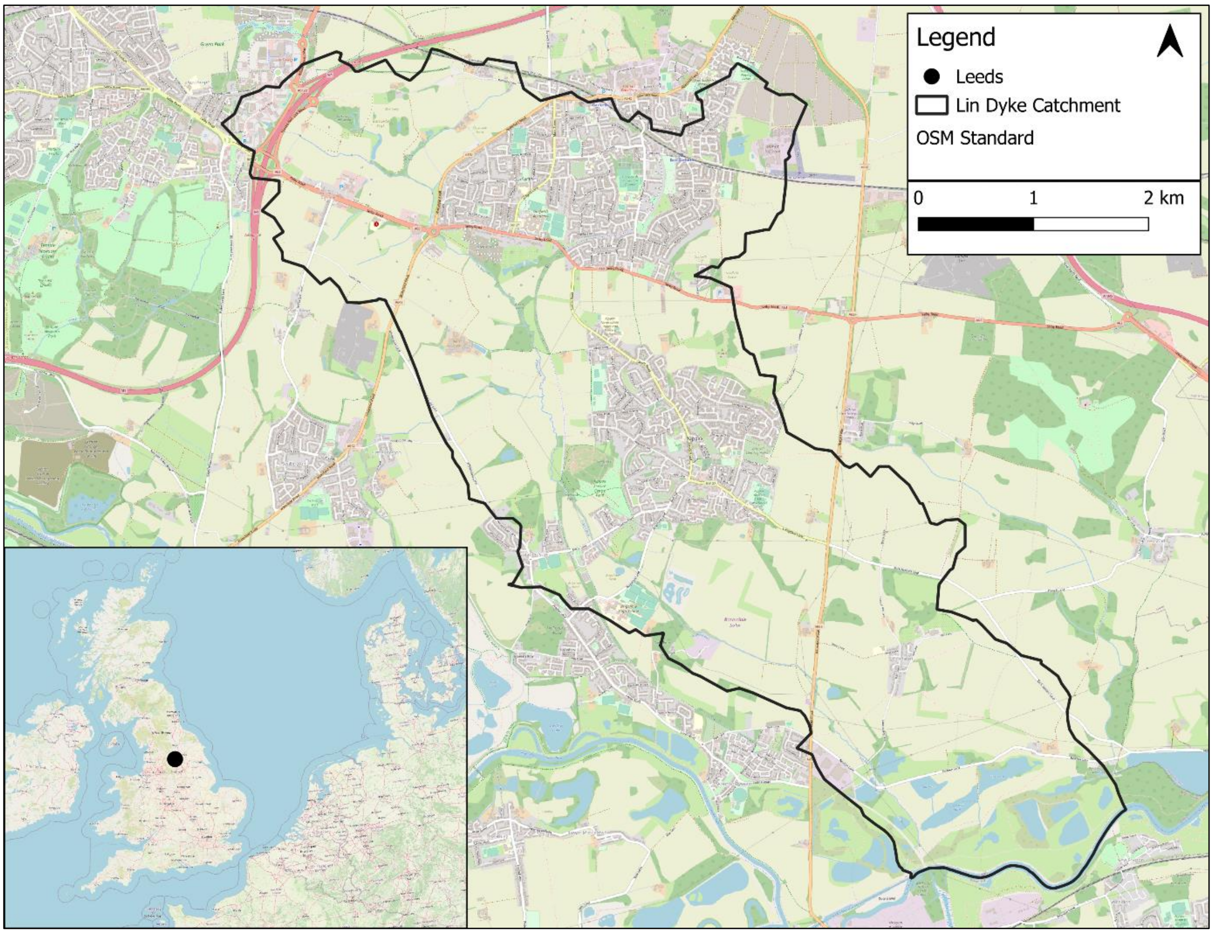

Figure 6-1: Location of Lin Dyke catchment

6.2.2 Modelling

All modelling was conducted using version 6.3.1 of the Hydrologic Engineering Centres River Analysis System (HEC-RAS). The software was used to run 2D rain-on-grid simulations for the Lin Dyke catchment, where rainfall for a 1-in-100-year return period is directly applied over the study area. The inputs used to model the Lin Dyke catchment were a digital elevation model (DEM) at 2 meters resolution, land use and net hyetograph. The DEM was adjusted to represent buildings by identifying the cells that overlapped with building vectors defined by OS Mastermaps; these building footprints were raised in elevation by 5 m to ensure that water flows around these structures. Additionally, kerbs were inserted by assuming a uniform kerb height of 10 cm to represent urban morphology. The UFR approach was then applied to the three scenarios in **Table 6-1**.

Table 6-1: Data sources used for model build.

Dataset	Source	Format	Description
DEM	Environmental Agency	Raster	LiDAR composite DTM
Catchment Boundary	UK Centre for Ecology and Hydrology	Vector	Outlines the boundary for the catchment obtained from the FEH web service
Land Use	OS Mastermap	Vector	Details of various land-use types within the study area
Rainfall Input	ReFH2	CSV	Design storm profiles for various drainage capacity allowances.

Table 6-2: Three scenarios applied to the Lin Dyke Catchment for the UFR approach

Scenario	Description
Baseline (BL)	where drainage capacity is 12 mm/hr applied across the whole model domain for a 1-in-100-year return period.
Baseline +Climate Change (BL+CC)	where drainage capacity is 12 mm/hr applied across the whole model domain for a 1-in-100-year return period plus a 45 % uplift for climate change allowance.
Baseline+ Climate Change + Drainage (BL+CC+DR)	where drainage capacity is applied using the CAF hexagon scores for the 2080 epoch across the whole model domain for a 1-in-100-year return period plus a 45 % uplift for climate change allowance

The UFR approach involves four key steps, which has also been previously described in Chapter 1 and 2:

1. Baseline Assessment – Here, the catchment response for a 1 in 100-year return period event is generated to establish the flood risk within the catchment.
2. Catchment disaggregation –the catchment area is divided into 'units'. These can be in the form of subcatchments or cells of varying sizes. For this paper, Voronoi polygons were used to

divide the Lin Dyke catchment into approximately 1 km^2 units; this method was used to avoid significantly smaller units at the edge of the catchment boundary, which generally occurs when using grid/cells **(Figure 6-2**)

UFR analysis - rainfall is omitted from each unit successively, and the model is run iteratively. Index generation: Each unit is ranked based on its contribution to flood risk within the catchment. For this paper, all depth and velocity outputs produced from the model runs of each scenario were classified using the Australian Rainfall Runoff Hazard categories ((Cox et al., 2010).

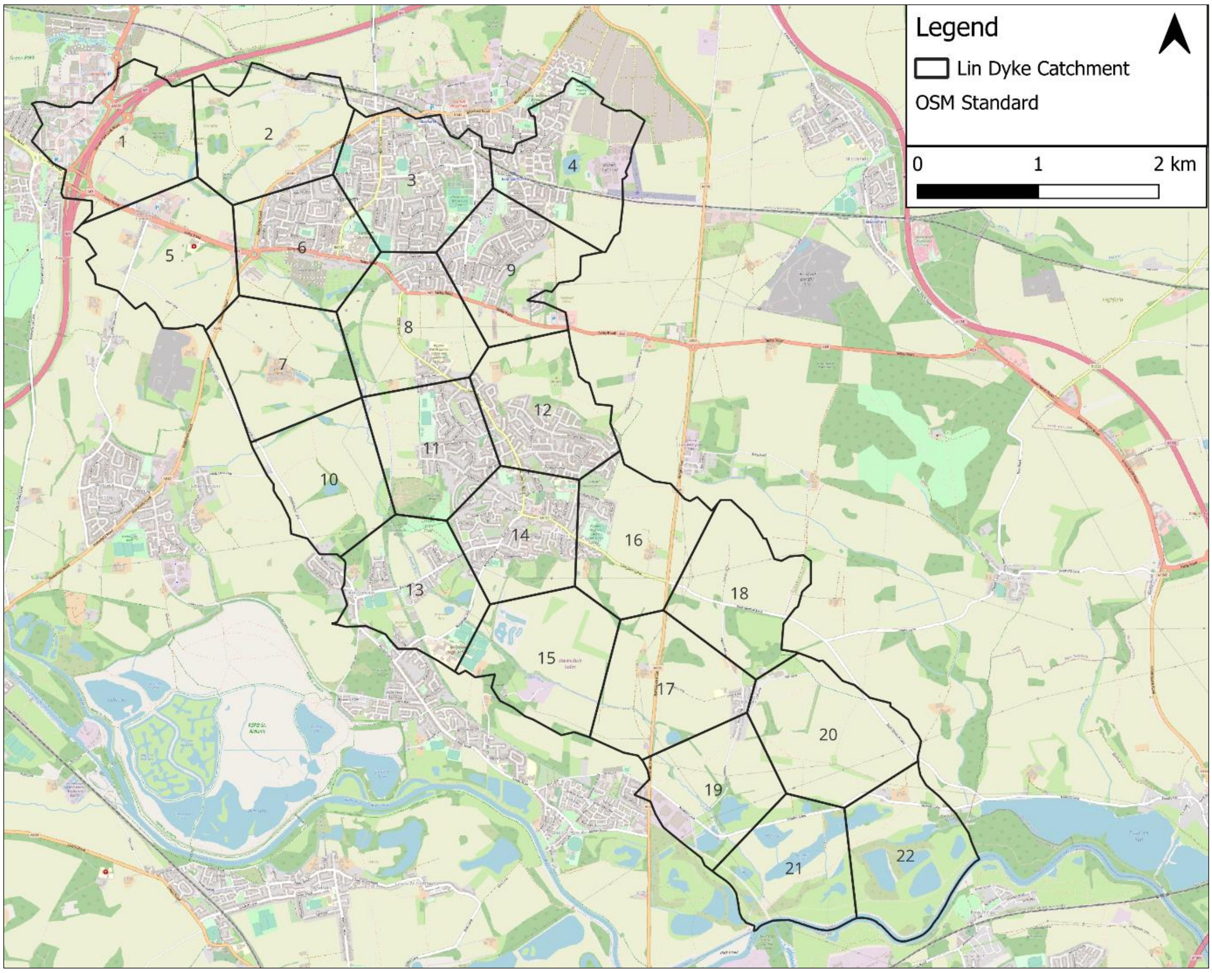

Figure 6-2: The disaggregation of the Lin Dyke catchment for applying the UFR approach using Voronoi polygons.

Following this, an index was generated by calculating the difference between the baseline and each iterative run for each scenario described in Table 6-2. Two criteria were used to generate the index, the detailed method for which has been provided in section Chapter 3:

1. Hazard Index (HI), where units are ranked based on their contribution to the overall hazard extent using the ARR classification H2 to H6, H1 is omitted as depth and velocity for that classification is generally considered safe for people, vehicles and structures.

2. Building Exposure Index (BEI), where units are ranked based on the number of buildings exposed to ARR classification of H5 and H6, which is considered unsafe for all buildings.

6.2.3 Hydrology

All net-hyetographs were created using the Revitalised Flood Hydrograph (ReFH2). The ReFH2 uses the physical attributes of a catchment to estimate rainfall depth for a required frequency and duration. The ReFH2 method was used to derive a design storm for a 1-in-100-year return period of 6.25 hours and a temporal resolution of 15 minutes. To assess the impact of the drainage system and climate change on identifying source areas using the UFR approach, net photographs were extracted for the scenarios (**Figure 6-3)**. Drainage for the BL and BL+CC scenarios was set at the national average capacity of 12 mm/hr(Environment Agency, 2013; Environment Agency, 2019) . For scenario 3 (BL+CC+DR), the CAF was used to interpolate capacity based on the risk score (on a scale of 1-5) per hexagon using the methodology described in Singh et al. (2023). A 45 per cent upper-end allowance of a climate change uplift factor was applied to the BLCC and BLCCDR hyetographs per the EA guidance on climate change allowances for this region (Environment Agency, 2019). Additionally, the 2080 epoch hexagons were used to derive the drainage capacity for the BLDRCC scenario.

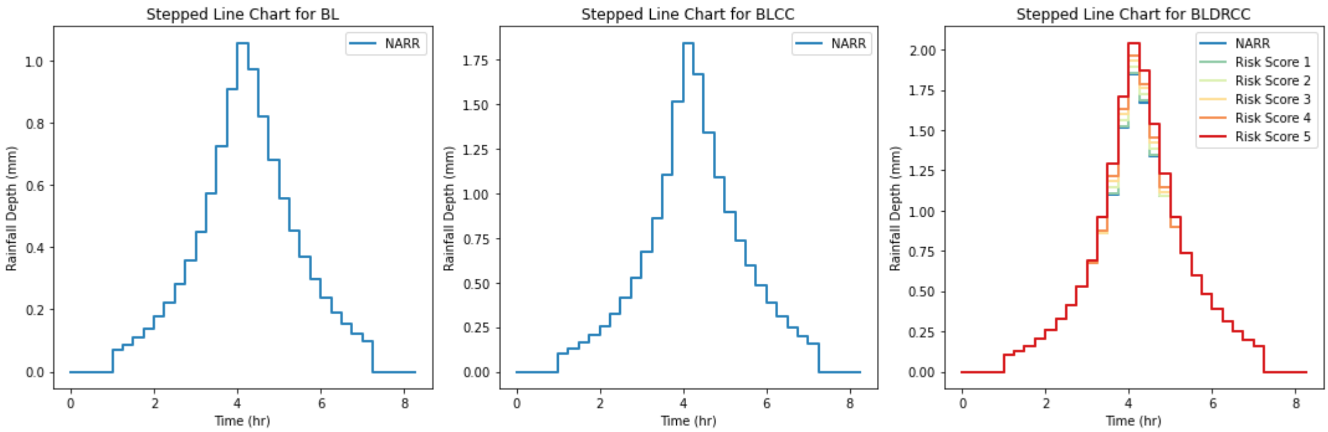

Figure 6-3: 1-in-100-year net-hyetograph used for the B, BLCC and BLCCDR scenario.

6.2.4 Analysis

The coverage calculation quantifies the CAF hexagon risk score for each subunit for the 2080 epoch. The spatial join operation in QGIS was used to associate the risk score attributes from the hexagon layer with the corresponding subunits based on their spatial relationship to perform this. For a risk score category, the three of each hexagon was calculated using the equation:

$$Hexagon\ Area = \frac{3\sqrt{3}}{2} x\ side\ lenght^2$$

Equation 21

Following this, the area of the interaction between each subunit and the hexagons corresponding to each risk score was calculated. For each subunit and risk score category, the coverage percentage was calculated using the following formula:

$$Coverage\ Percentage\ =\ (Area\ of\ Intersection\ /\ Area\ of\ Subunit)\ *\ 100$$

Equation 22

Finally, the total coverage percentage for each risk score category was aggregated.

The following equation was used to calculate the relative change of the rankings from the different scenarios.

$$Relative\ Change = \frac{(New\ Values - Old\ Values)}{Old\ Value}$$

Equation 23

The rank stability was used to quantify how stable the ranking positions were for each subunit across the different HI and BEI rank scenarios. To calculate the rank stability, the standard deviation of each of the ranks across the different scenarios was calculated using the following formula:

$$Rank\ stability = \frac{\sqrt{(\Sigma(Rank - Average\ Rank)^2}}{(Number\ of\ Scenarios - 1\ ))}$$

Equation 24

Where *Rank* refers to the individual ranks assigned to a specific unit, the *average rank* is the mean of all the ranks across the scenarios, and the number of scenarios is the total number of considered scenarios, i.e., 3.

Kendall's Tau-b correlation coefficient measures the relationship's strength and direction between two rankings. To calculate the Kendall Tau-b correlation, the number of concordant and discordant pairs between the ranking and the following equation was applied. Concordant pairs are those that have the same order in rankings, and discordant pairs are those that have different relative orders in rankings.

$$Kendall's\ Tau - b = \frac{nc - Nnc}{\sqrt{nc} * nd}$$

Equation 25

Where *n* is the number of *c* is concordant pairs, and *d* is discordant pairs.

The resulting Kendall's Tau-b correlation coefficient ranges from -1 to +1. Positive values indicate a positive correlation, negative values indicate a negative correlation, and values closer to 0 suggest weaker or no correlation.

6.3 Results

6.3.1 CAF risk score coverage.

Figure 6-4 plots the coverage of different risk scores for each subunit; this indicates the drainage capacity associated with urbanised subunits, specifically subunits 3, 4, 6, 8, 9, 11, 12, and 14 (see **Figure 6.2** for locations) that are dominated by grey space (i.e., impermeable surfaces). The graph shows that most subunits are covered by a hexagon risk score of three, indicating that 30% to 45% of pipe length will exceed capacity. Based on the coverage analysis, subunit 2 has a high coverage for risk score 2, while subunit 8 has a high coverage for risk score category 3. Subunit 3, which is highly urbanised, has a high coverage for risk score categories 3 and 4. Subunits 2, 10, 16, 20, 21 and 22 have a high coverage of risk score zero, i.e., no data.

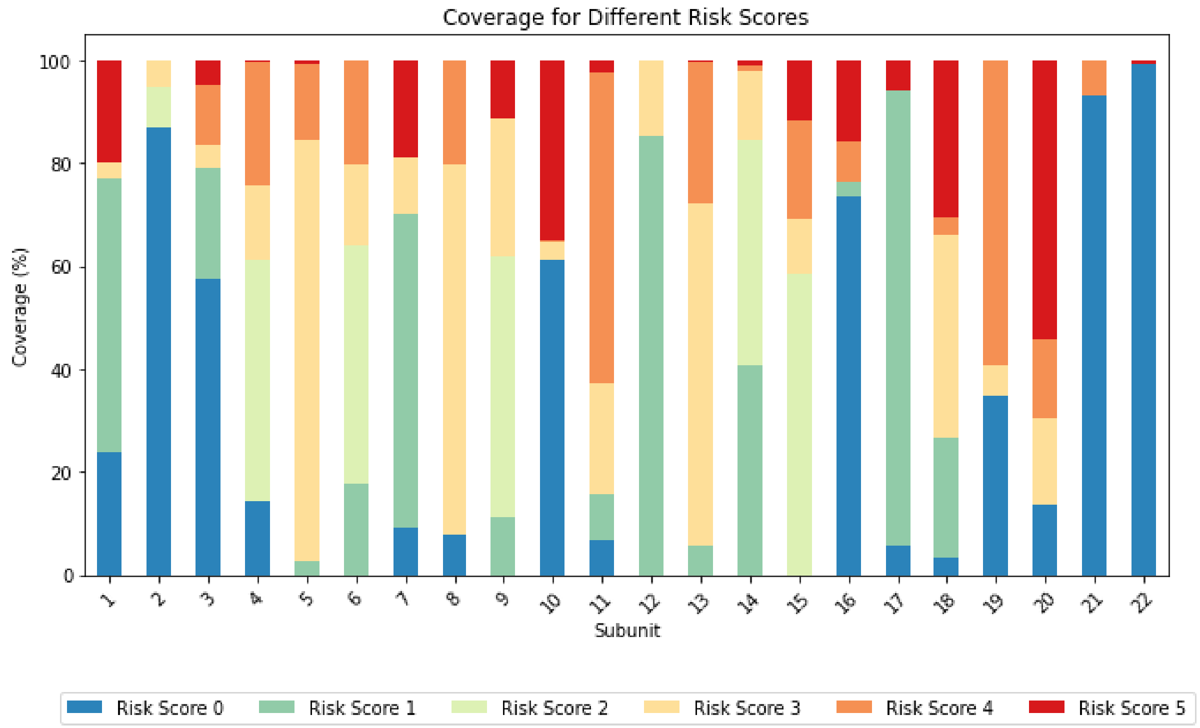

Figure 6-4: Risk coverage of Lin Dyke subunits based on CAF framework subunits refer to the subunits presented in Figure 6.2.

6.3.2 Hazard Index (HI)

These rankings represent the order of subunits based on their contribution to hazard extent as calculated based on the ARR. The HI ranks show that subunits 2, 5, and 6 consistently rank high across all three scenarios. The subunits closer to the outlet, i.e., 19, 20, 21, and 22, consistently rank low across the three scenarios. Based on the rank stability, subunits 4 and 2 show the most significant variability in the ranks across the different scenarios. The results also show that BL and BLCC have a moderate positive relationship (0.54), BL and BLCCDR have a stronger positive correlation of 0.59, and BLCC and BLCCDE have a moderate positive correlation of 0.47. **Table 6-3** shows the ranking of each subunit across the BL, BLCC and BLCCDR scenario and the relative change from the BL to BLCC scenario and the BLCC to BLCCDR scenario. **Figure 6-5** shows the spatial distribution of the ranks across the three scenarios. The HI rank maps also show that the subunits located south of the catchment rank low consistently across the catchments. In this case, the rank stability measures the consistency of how the subunits are ranked across the scenarios.

Table 6-3. Relative change and the Rank stability (%) of Lin Dyke subunits across the three scenarios (calculated from equation 20).

HI						
Subunit	**BL**	**BLCC**	**BLCCDR**	**Relative Change_BLCC**	**Relative Change_BLCCDR**	**Rank Stability**
1	3	10	2	2.33	0.33	4.36
2	1	11	3	10.00	2.00	5.29
3	13	12	6	0.08	0.54	3.79
4	20	9	18	0.55	0.10	5.86
5	2	1	1	0.50	0.50	0.58
6	4	2	4	0.50	0.00	1.15
7	7	4	4	0.43	0.43	1.73
8	16	8	10	0.50	0.38	4.16
9	22	18	19	0.18	0.14	2.08
10	8	5	12	0.38	0.50	3.51
11	10	6	14	0.40	0.40	4.00
12	5	13	7	1.60	0.40	4.16
13	6	3	13	0.50	1.17	5.13
14	9	14	16	0.56	0.78	3.61
15	18	16	9	0.11	0.50	4.73
16	11	7	8	0.36	0.27	2.08
17	12	17	11	0.42	0.08	3.21
18	14	15	17	0.07	0.21	1.53
19	19	19	20	0.00	0.05	0.58
20	15	20	15	0.33	0.00	2.89
21	17	21	22	0.24	0.29	2.65
22	21	22	21	0.05	0.00	0.58

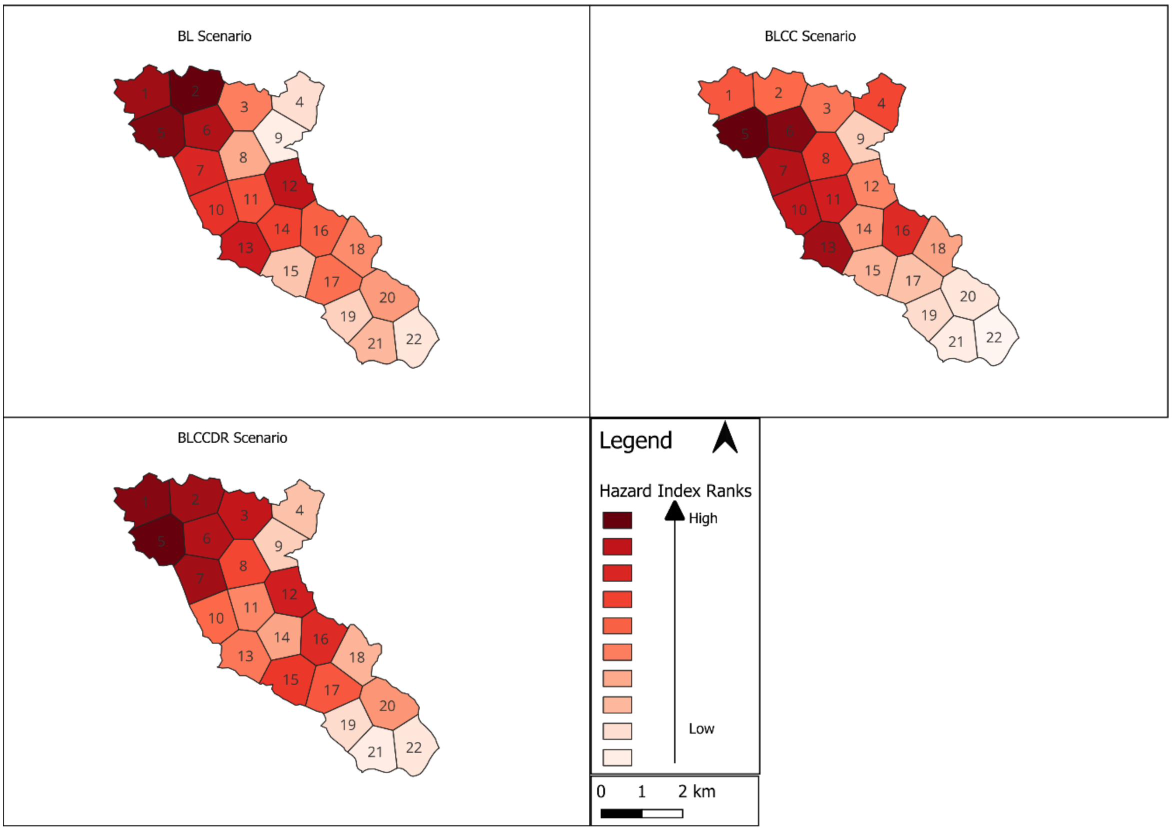

Figure 6-5: The HI ranks of the subunits for the Lin Dyke catchment for the BL, BLCC and BLCCDR scenarios; dark shades of red indicate that the units rank high on the index and lighter shades of red show lower ranks

6.3.3 Building Exposure Index (BEI)

For the BL, BLCC, and BLCCDR scenarios, when all units receive rainfall, the total number of buildings that flood is 97, 134, and 136. This shows that the increase in rainfall due to the inclusion of climate change projections increases the number of buildings flooded by 38.14 %; the inclusion of drainage capacity presentation using the CAF resulted in a 1.47% increase in the number of buildings flooded. **Table 6-4** and **Figure 6-5** presents the ranking of the subunits, the relative change and the rank stability calculated from the BEI. Based on the BEI ranks, subunit nine consistently ranks low in all scenarios, ranked the lowest in the BL and BLDRCC scenarios and 7th in the BLCC scenario. Subunits 5, 6, 7, and 8 show the most significant variability in the rankings. Based on the rank stability, subunits 3 and 16 show high variability in the overall rankings between the different scenarios. The results also show that for Kendall's tau-b correlation, there is a moderate positive correlation of 0.58 between the BL and BLCC scenarios. A strong positive correlation (0.88) between the BL and BLCCDR scenario indicates that the BEI rankings are closely aligned between the two scenarios, and lastly, a 0.61 moderate positive relationship between the building hazard rankings under the BLCC and BLCCDR scenario.

Table 6-4: Relative change and the Rank stability (%) of Lin Dyke subunits across the three scenarios (calculated from equation 21

Building Exposure Index						
Subunit	**BL**	**BLCC**	**BLCCDR**	**Relative Change BLCC**	**Relative Change BLCCDR**	**Rank Stability**
1	4	7	4	0.75	0.00	1.73
2	17	16	13	0.06	0.24	2.08
3	2	11	2	4.50	0.00	5.20
4	2	1	3	0.50	0.50	1.00
5	7	4	7	0.43	0.00	1.73
6	5	2	5	0.60	0.00	1.73
7	9	5	5	0.44	0.44	2.31
8	6	3	8	0.50	0.33	2.52
9	1	7	1	6.00	0.00	3.46
10	17	9	15	0.47	0.12	4.16
11	13	7	13	0.46	0.00	3.46
12	11	14	11	0.27	0.00	1.73
13	9	5	8	0.44	0.11	2.08
14	7	13	8	0.86	0.14	3.21
15	17	20	19	0.18	0.12	1.53
16	17	9	19	0.47	0.12	5.29
17	14	17	15	0.21	0.07	1.53
18	14	17	15	0.21	0.07	1.53
19	11	15	12	0.36	0.09	2.08
20	17	20	19	0.18	0.12	1.53
21	17	20	19	0.18	0.12	1.53
22	14	17	15	0.21	0.07	1.53

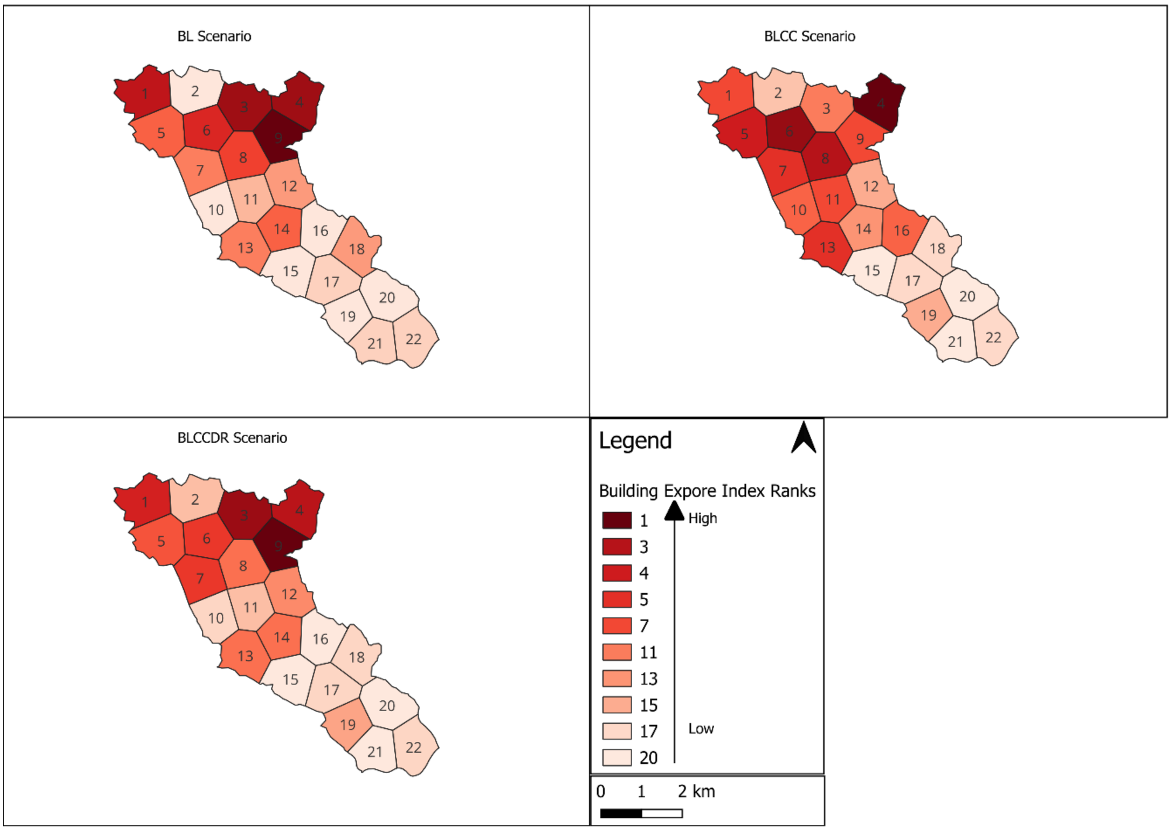

Figure 6-6: The BEI ranks of the subunits for the Lin Dyke catchment for the BL, BLCC and BLCCDR scenarios; dark shades of red indicate that the units rank high on the index and lighter shades of red show lower ranks

6.4 Discussion

The change in rankings of the hazard extents shows that overall, subunits within the Lin Dyke catchment consistently maintain their ranks across the BL, BLCC and BLCCDR scenarios. For instance, Subunit 5 maintains a consistent trend in high ranks across the three scenarios. Based on the results, stable units provide a reliable baseline for flood risk assessment and can be used to inform decision-makers when planning mitigation strategies. Several subunits change rankings across all scenarios. For example, subunit 9 experiences a significant change in rankings across the three scenarios. In the BL scenario, subunit nine is ranked 22nd, followed by 18th in the BLCC scenario, suggesting that subunit 9 becomes more susceptible to flooding, leading to a higher ranking under the influence of climate change. In the BLDRCC scenario, subunit nine further changes its rank to 16th, implying that not only does climate change impact the subunit's contribution, but representing drainage capacity exacerbates its vulnerability. Several factors influence this change, one being that the representation of the drainage capacity using the CAF highlights that the subunit lacks an effective drainage system; this is further supported by subunit nine, which significantly consists of residential developments and, hence, grey space. Subunit 9 provides an excellent example of how the UFR approach can drive adaptive flood risk management. Furthermore, this example shows how the subunits' ranking can shift based on factors considered, such as climate change and drainage capacity representation.

Since their contributions are relatively stable across scenarios, these areas can be ideal locations for when management investments will offer the most significant benefits. For instance, subunit 11 is a highly urbanised area with grey infrastructure. This subunit maintains a ranking of 7 across all scenarios, indicating its consistent nature in contributing to hazards; hence, this information can be used to focus FRM strategies on a densely urbanised area. The main aim of this paper was to investigate the combined effects of UDS and CC on FSAs using the UFR approach. Within this context, the UFR approach proved to be an ideal framework that can be used for dynamic FRM. The results indicated that the representation of drainage infrastructure and drainage system capacity does influence the contribution of flood hazards posed by subunits within the Lin Dyke catchment.

The additional analysis on the FI and BEI provides a foundation for targeting long-term FRM measures and how the tool can be used to direct investments and strategies effectively. Most of all, the approach has highlighted that flood risk and the hazards associated are not static, and vulnerability to the risk associated with flooding within the catchment will increase under climate change scenarios and inadequate infrastructure. Additionally, the approach drives its users to focus on the unique characteristics of the subunits (e.g., is it urban/rural?). Hence, if the UFR approach is aligned with dynamic FRM, such as mobile flood barriers that respond to changing flood patterns, it can become an integral part of flood risk management in urban planning and promote effective FRM suitable even in the face of changing flood risk.

Spatially subdivided flood risk assessment approaches such as UFR can provide more detailed insights into a catchment's flood risk by enabling local variations in rainfall patterns and their impact on different areas. By accounting for this spatial variation, obtaining a more realistic representation of flood risk and identifying areas particularly sensitive to specific rainfall patterns is possible. Hence, it is essential to continuously improve this methodology to include the complexities associated with spatial variation, not just in drainage capacity but also in rainfall patterns. Within this study, the spatial variation in the rainfall inputs is only associated with the drainage capacity. Hence, the method and understanding of flood risk within the catchment can be improved by representing the spatial variation in the rainfall itself.

Analysis of the HI and BEI ranks of the urbanised subunits, i.e., 3, 4, 6, 8, 9, 11, 12, and 14 for the BL, BLCC and BLCCDR scenarios show that the urbanised subunits rank consistently high. For example, the majority (87.6%) of the areas within subunit three are occupied by buildings, and it ranks within the top five for the HI ranks; even though the ranking for the BEI is variable, it is still relatively high. However, subunit 14, although urbanised, does not rank high across all scenarios because it is surrounded by subunits that consist of significant amounts of green space and have a lower mean elevation than that of subunit 3. These results indicate that although land use is essential, other physical aspects of the subunit also play a vital role in ranking the subunits and their contribution to hazards. Furthermore, the subunits' position and the surrounding subunits' physical parameters are also crucial in dictating the contribution of the subunit. For example, in this case the surrounding green spaces modify the response of the unit, demonstrating that integrating green areas with urban areas has a positive effect.

When comparing the difference in the number of actual buildings exposed to hazards under the BLCC and BLCCDR, it becomes apparent that the representation of drainage capacity using the CAF has a significant impact. This demonstrates that the interaction between rainfall and drainage capacity determines flood vulnerability. For example, applying the UFR approach for subunit 6 for the three scenarios shows drastic variability in the number of buildings exposed to hazards compared to the baseline assessment. Initially, in the BL scenario, subunit 6 exposes ten additional buildings to hazard; this is increased to 47 under the BLCC scenario and then reduced to 11 in the BLCCDR scenario, i.e., a 77% decrease. This reduction is due to the CAF's representation of the drainage system capacity. Through this example, it is demonstrated that specific subunits are more susceptible to climate-change-induced flooding. However, representation of the drainage system capacity is essential when investigating flood hazards and exposure in urban areas.

The combined hazard scores indicated that subunits 9, 16, 6, 8 and 7 should be the top five subunits in order of rank importance for FRM both now and under climate change scenarios. Subunits 9 and 6 are relatively urbanised; although less urbanised, the remaining three have higher elevations and are surrounded by highly urbanised subunits. Additionally, the area of subunits 8 and 7 is overlain by CAF hexagons with a risk score of 5, indicating that some pipes within these subunits will experience significant surcharge.

A limitation identified through this study is that several units were tied when establishing the BEI ranks; the results for this study only had tied BEI ranks for subunits with 0 buildings; hence, no tie-breakers were applied. However, applying the UFR methodology has not addressed a logical or systematic solution to a situation when subunit ranks are identical. To address this, there needs to be a methodology that establishes a tie-breaking criterion. The methodology could use secondary risk metrics such as historical flood data as tiebreakers. Physical characteristics such as land use, elevation soil type or proximity to emergency routes can also be critical factors to break ties and establish a priority index for the subunits. Further sensitivity analysis where weights are assigned to these different parameters and their influence on rank changes can help identify which criteria influence ranks most and can be used as tiebreakers.

6.5 Conclusions

This paper presents the first application of the UFR approach using 2D hydrodynamic modelling with representation of climate change and drainage capacity for the catchment of Lin Dyke. The results highlight the dynamic nature of flood source areas within the Lin Dyke catchment, as they shift in response to factors such as climate change and drainage capacity representation. Some subunits consistently rank high, while some fluctuate emphasising the demand for adaptable FRM strategies, with the UFR approach providing a structured mechanism for adaptive decision-making. The positive correlations between ranking across scenario show that some subunits are persistent in their ranking and due to the stability of their contribution to HI and BEI they should be prioritised for FRM interventions. Regarding practical applications, subunits consistent in their rankings offer opportunities as locations suitable for long-term FRM measures. In contrast, subunits that consistently change ranks across scenarios require additional attention and further investigation.

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Chapter 7 Synthesis

7.1 Introduction

The of this thesis was to advance the use of 2D hydrodynamic models for the approach and explore the relevancy of the methodology for urban catchments. Additionally, the thesis also aimed to develop and apply a nationally applicable methodology for drainage representation flood models and assesses its impact in the context of flood source area identification. To achieve this aim, the following objectives were identified:

1. **To conduct a comparative investigation of how different models, such as TUFLOW and HEC-RAS identify FSAs using the UFR approach.**
2. **Develop a methodology for representing UDS drainage system in flood models.**
3. **Investigate the combined effects of UDS and CC on FSAs using the UFR approach.**

From the objectives of this research, three key research questions were identified in Chapter 1, these were:

1. How do FSAs differ when applying the UFR approach using different hydrodynamic models?
2. How can we improve representation of drainage systems in urban flood models?
3. To what extent can drainage representation within the context of the unit flood response approach improve assessments for flood risk management under climate change scenarios?

In this chapter, the main findings that are relevant to addressing these research questions from across all chapters are combined into a synthesis showing how this improves our overall understanding related to this research topic. The synthesis includes a discussion on the findings and limitations that have been identified.

7.2 How do FSAs differ when applying different hydrodynamic models?

The literature review conducted in Chapter 2 highlighted various methodologies used to identify flood source areas within a catchment. Through an extensive analysis of existing literature within this topic, two prominent approaches emerged as key strategies for identifying FSAs. The first approach, known as the UFR methodology, uses an iterative modelling process aimed at comprehending the interplay between different areas of the catchment and their overall influence on flood risk. This methodology emphasises a systematic examination of factors to gain a comprehensive understanding of the flood dynamics within the catchment. The second approach, termed the ADA, uses mostly the physical characteristics of a catchment to estimate the areas that contribute the most to flooding and uses this to drive adaptive measures that should be implemented within the chosen catchment. By considering a range of factors such as topography, land use patterns, and hydrological properties, ADA provides valuable insights into the specific regions within the catchment that are more likely to act as primary sources of flooding. This approach emphasises the assessment of the catchment's inherent attributes and their relationship to flood generation, enabling the identification of key areas that significantly impact flood risk.

A common element among all the approaches to identify flood source areas is the reliance on numerical flood models as tools to identify FSAs. The advances in computing, such as highly parallelised computing and the utilisation of GPU cores, have significantly enhanced the capability to execute larger and faster models (Kalyanapu et al., 2011; Liang et al., 2016; Hou et al., 2020; Buttinger-Kreuzhuber et al., 2022). Despite these computational advancements facilitating the application of large-scale models, the UFR approach has not been extensively explored with 2D models, particularly for large urban catchments. Previous studies applying the UFR approach have been limited, with Vercruysse et al., (2019) being the only study to utilise it in a 9 km^2 study area in Newcastle-upon-Tyne. Furthermore, the ADA approaches have been particularly used in areas where the presence of drainage infrastructure plays a crucial role in identifying flood source areas. For example, the latest publication within the topic of FSA (Wu et al., 2023).

In Chapter 3, the use of more recent methods of flood modelling i.e., RoG models for urban catchments, was assessed to enhance our understanding of the UFR approach's applicability. This chapter aimed to provide insights into the challenges associated with utilising modelling tools within the UFR approach and to assess the model independence of the UFR approach. Specifically, it aimed to determine whether the ranking of importance for identified flood source areas remains consistent between different software platforms. By evaluating the capabilities and limitations of various modelling tools, this research has yielded valuable insights outlined below into the effectiveness of RoG modelling in the context of flood source area identification within the UFR approach.

The research conducted in Chapter 3 used TUFLOW and HEC-RAS as modelling tools to apply the UFR approach using the RoG methodology. Key reasons for the choice of these two software suites were that they are established and trusted, they have comprehensive functionality and are widely accepted by regulatory agencies (Néelz and Pender, 2013; Costabile et al., 2021). It was found that the methodology could be implemented relatively easily with both software packages, however, it was computationally demanding due to the requirement of iterating through multiple scenarios, this was especially highlighted when using HEC-RAS.

A significant contribution of Chapter 3 was the first multi-model comparison of the UFR approach for the same catchment. The findings reveal that the ranking of subunits changes depending on the software used, emphasising the importance of considering the choice of software when applying the UFR approach and interpreting the results. The variations in predictions between different flood models introduces uncertainty into the decision-making process. Decision-makers rely on accurate and reliable information to formulate effective flood risk management strategies. When different models produce different results, it becomes challenging to determine which predictions are the most trustworthy. This uncertainty can hinder the ability to make informed decisions and allocate resources effectively (Kellens et al., 2013). Furthermore, the postprocessing methodology in this study expands the UFR methodology which has previously been applied to focus beyond flooded areas, incorporating hazard categorisation and exposure assessment. This provides an alternative way of ranking subunits based on specific priorities, which may offer a more suitable and practical measure for flood risk management strategies. To enhance the robustness and practical application of the UFR approach, it is crucial to investigate the requirements of decision-makers and how the UFR approach can be effectively utilised in flood risk management (FRM) practice. Understanding the needs and perspectives of decision-makers is instrumental in refining the methodology, as their reliance on flood predictions simulated by models is pivotal for planning and implementing effective flood risk management measures.

In addition to limitations mentioned above, there are other issues introduced by omitting rainfall from certain areas of a catchment during simulating and addressing flood behaviour within the catchment. Omitting rainfall from certain areas of a catchment during flood modelling provides an incomplete representation of hydrological processes(Ochoa-Rodriguez et al., 2015). Rainfall is a crucial input for flood modelling as it drives the hydrological processes that lead to flooding. By omitting rainfall from certain areas, the model fails to capture the full spatial distribution of precipitation and its impact on runoff generation within the catchment. This incomplete representation can lead to inaccurate simulations of flood peaks, flood extents, and the overall flood dynamics.

Additionally, in its current form the approach does not consider socio-economic parameters. For instance, source areas are identified based on their contribution to flood risk, however, the priority ranking neglects the socio-economic conditions of these units. If the rankings are used to drive decision making and implementation of FRM, neglecting the socio-economic conditions within a subunit can exacerbate existing equity issues posed by flood risk, leading to inadequate protection and increased vulnerability for the communities residing there. If the UFR approach is used to drive decision-making, the topic of socio-economic gap needs to be addressed. Socio-economically disadvantaged communities are known to face higher vulnerability to floods due to factors such as limited resources and inadequate infrastructure (Kaźmierczak and Cavan, 2011; da Silva et al., 2012; Gan et al., 2021; Lindersson et al., 2023). Hence, the choice of parameters that are used for the UFR approach to derive the rankings needs to also consider social and economic factors to provide a holistic overview of FSAs and support effective FRM measures.

7.3 How can we improve representation of drainage systems in urban flood models?

Another key research gap identified in the application of not just the UFR approach, but also urban flood modelling, was the representation of drainage in systems in urban flood models. Hence to address this research gap, Chapter 4 introduced the CAF datasets as a potential tool to improve our representation of urban drainage systems in flood models. Common methods that are used to represent drainage systems in flood models include the rainfall reduction approach, whereby a 12 mm/hr rainfall depth is removed from the hyetograph to represent losses to the drainage system. Other methods include using synthetic generation of urban drainage, and inlet drainage approach which has been previously described in Chapter 1 (Möderl et al., 2009; Bertsch et al., 2017b; Li et al., 2023). Chapter 4 provides a thorough understanding of the method involved in the creation of the CAF dataset. Furthermore, the chapter provides an understanding of the actual drainage capacity of the city of Leeds. The dataset not only provides information regarding the capacity of the drainage system for the current time but also for future epoch under climate change scenarios i.e., 2030, 2050 and 2080.

Local spatial autocorrelation was used to identify spatial patterns within the data set for the city of Leeds. The analysis indicated that hexagons with high risk levels that underperform in 2020, are related to the capacity and performance of the surrounding hexagons, this leads to an increase in their risk scores for future epochs. This suggests that the proximity of a hexagon with poor capacity is an important factor in determining the performance of pipes in adjacent hexagons. Understanding these spatial patterns and network connectivity is crucial for effective prioritisation of resources and interventions. Overall, the analysis of the CAF outputs revealed a general decrease in the capacity of the drainage system within Leeds. This decline can be attributed to factors such as climate change, population growth, and urbanisation.

Chapter 5 focused on developing a methodology to use the CAF data set directly in urban flood models. The developed method was then applied to three urban catchments in Leeds, namely: Holbeck, Wyke Beck and Lin Dyke. The methodology used a linear relationship to estimate the drainage losses based on the risk score for each of the catchments. These values were then used to derive hyetographs with different drainage losses that served as an input to HEC-RAS 2D models for RoG for each of the study areas. The findings demonstrated that the application of the CAF dataset to represent drainage systems led to an increase in rainfall inputs used for flood modelling. However, this increase in rainfall inputs did not always result in a corresponding increase in flood extent. The disparity in flood risk extent and magnitude can be attributed to the unique characteristics of each catchment, including factors such as urban extent, topography, and the number of hexagons with high-risk scores. Three return periods and two scenarios for each return period were used to illustrate the application of the CAF dataset and its impact on flood risk assessments. The results revealed that, for two out of three catchments, flood risk moderately increased when using the CAF-derived rainfall removal rates for drainage representation. However, the catchment of Lin Dyke exhibited significant local variations in flood risk when using the CAF dataset.

The results also indicated that on average (i.e., overall), the model results were not substantially affected by the variable representation of drainage removal rates derived from the CAF dataset. Nevertheless, even minor differences in drainage representation can have significant implications for flood risk management strategies, future developments, and investments, particularly at a local scale. The three case studies that were used in this research, exhibited different responses to the use of CAF-derived drainage representation. This suggests that the value of drainage representation in flood models is contingent upon the specific catchment, its location, and the scale of analysis. Consequently, it is crucial to apply the CAF dataset and the methodology outlined in this study to other catchments across the UK to comprehend the broader implications of this dataset and methodology. This will facilitate the understanding and quantification of the effects of variable drainage representation in flood models. Additionally, conducting case studies is essential for identifying catchments with specific parameters that exhibit greater sensitivity to drainage representation.

The methodology present in Chapter 5 is still in its early stages, presenting significant opportunities for further research and application. One area of focus is the improvement of methods used for drainage capacity estimation. It was observed that the linear interpolation technique led to an increase in the drainage capacity allowance when the red length of pipes in the network was larger. Consequently, alternative, and more appropriate methods should be explored such as nonlinear regression, which allows for more flexible modelling of the relationship between risk scores, red length pipes and drainage capacity estimation. Algorithms such as polynomial regression also have the potential to capture the complex patterns present in the dataset and provide a better fit to the data. Another aspect that requires attention is the handling of hexagons with missing data within the dataset, therefore, geospatial techniques, such as kriging or spatial regression, have the potential to address this issue and should be investigated. These methods consider the spatial correlation between neighbouring hexagons and can provide predictions for locations based on the information from nearby hexagons.

By applying these alternative techniques, the dataset can be reconstructed to include estimates for hexagons that lack data, enhancing the overall completeness and reliability of the dataset. Furthermore, it is essential to assess and apply alternative approaches to evaluate their performance in estimating drainage capacity using the CAF dataset. Comparing different methodologies and results, enables us to investigate and gain insight into the strengths and limitations of each approach, leading to the refinement and improvement of representing drainage systems in urban flood models. In addition to methodological considerations, there is also the potential to create a similar dataset for low-income countries, where data scarcity is a significant challenge. In doing so, we will be able to understand the applicability and transferability of generating the CAF dataset by addressing this data gap, the application of the CAF dataset can be extended to a broader range of regions, enabling better flood modelling and risk assessment in areas where comprehensive data is currently lacking.

7.4 To what extent can drainage representation within the context of the unit flood response approach improve assessments for flood risk management under climate change scenarios?

Further to the research gaps highlighted in Chapter 1 and Chapter 2, the work presented in this thesis advances the understanding of the UFR approach by its application to climate change scenarios. Chapter 5 investigated impact of utilising climate change scenarios to identify FSAs by applying the UFR approach. The findings presented in this chapter investigate the effectiveness and robustness of the UFR approach in capturing the potential changes in flood risk under various climate change scenarios. Moreover, the methodology used to answer this research question extends beyond the conventional approach by considering the representation of drainage systems in conjunction with climate change projections. By incorporating a combination of climate-induced alterations and drainage system capacity, the findings in this chapter helped improve the understanding of how flood risk is influenced by both climatic factors and the capacity of the drainage system.

To address this objective, the Lin Dyke catchment was used as it showed the most sensitivity to drainage representation and is shown in Chapter 5. Overall, a climate change uplift of 45 % was applied to the rainfall and the CAF dataset for the 2080 epoch was used to represent drainage systems. Following this the methodology outlined in Section 5 was applied to implement the CAF dataset in the modelling framework. The results showed that the rankings of subunits provide insights into their relative contribution to overall flood risk when comparing rankings across different scenarios, such as the baseline (BL), climate change (BLCC), and climate change with drainage representation (BLDRCC) scenarios, helped identify the areas that have the most significant impact on flood risk. The comparison of the rankings between the BL and BLCC scenarios demonstrated changes in subunit rankings indicate shifts in flood risk patterns due to the inclusion of climate change factors. The BLDRCC scenario, which incorporates both climate change and drainage representation, further highlights the combined effect on flood risk.

Calculating the relative change and cumulative change provided quantitative measures of the differences in flood risk contribution between scenarios showed a significant change in source areas from the BL and BLCC scenario and a small change when comparing the BLCC and BLDRCC scenarios. Additionally, the Kendall's tau-b correlation coefficients were used to assess the stability of rankings between pairs of scenarios. Higher coefficients indicated a higher level of stability in rankings, and lower coefficients indicate more variation. The stability analysis showed a moderate stability in the rankings of the subunits for Lin Dyke. Overall, the results highlighted the importance of considering climate change and drainage representation in the UFR approach to identify FSAs. Applying the CAF representation methodology also highlighted a limitation of the linear interpolation approach. The red lengths are dynamic and change per catchment and risk score. The length of red pipes for Lin Dyke increased under climate change scenarios, using this for the linear interpolation resulted in an increase in the capacity of hexagons that have a risk score of 5. For the case of Lin Dyke, a minor increase in the capacity was observed however, this was negated as a large area of the catchment was covered by hexagons that had a risk score of 5. However, for other catchments, this method will prove to be too simplified hence previous suggestions for further work are of utmost importance.

The CAF data set uses UKCP09, while the UKCP18 was used to apply the rainfall uplift to represent climate change. Although, UKCP09 was a significant advance in climate projections at the time it is now superseded by the UKCP18. Hence, further work by companies responsible for drainage needs to apply the UKCP18 to the CAF data set especially since UKCP09 had a relatively coarse spatial resolution of 25 km, which limited its ability to capture localised climate features and impacts accurately. In contrast, UKCP18 has a higher resolution of 2.2 km through the UKCP18 regional climate model, providing more detailed regional projections. Additionally, UKCP18 utilises updated climate models, such as the high-resolution HadGEM3 and the improved UKCP18-RR regional climate model which have a better representation of key climate processes, resulting in more accurate projections compared to the models used in UKCP09. The UKCP18 projections also include a wider range of climate variables compared to UKCP09 such as temperature, precipitation, and wind, humidity, and radiative fluxes. These additional variables offer an improved understanding of the climate system and allow for a more detailed assessment of climate impacts (Lowe et al., 2018; Met Office, 2019; Murphy et al., 2019).

7.5 Contribution to Science

Within the context of the UFR approach, I have contributed:

- To the methodological advancement of the UFR approach by integrating the UFR approach with hydrodynamic models like HEC-RAS and TUFLOW, I have advanced the methodology for flood risk assessment.
- To the understanding of the limitations and capabilities of the software within the context of the approach.
- To the improvement of risk assessment and prioritisation of high-ranking subunits by combining climate change scenarios and representing drainage systems. By analysing the results of these simulations for the catchment of Lin Dyke, I was able to investigate areas that contribute to flooding not only under current conditions but also under future climate change conditions.

Within the context of representing drainage systems in flood models, I have contributed to:

- The improved understanding of the impact of representing drainage systems in flood models by incorporating drainage data into flood models and quantify its impact on flood risk in urban areas.
- Bridging data gaps as drainage data is often limited or not readily available for many regions. By tackling the challenge of estimating drainage capacity using the CAF data set, I have bridged the data gap and provided a method to obtain drainage information in areas where it is lacking.
- The development of the methodology to use the CAF dataset to represent the capacity of drainage system in flood models contributes to the replicability and scalability of flood modelling efforts. The approach can be applied to other regions where the data set is available helping to standardise and generalise drainage capacity estimation techniques.

7.6 Implications for Flood Risk Management

This project focused on applying the unit flood response approach using RoG methodology and addressing research gaps such as the use of multiple models, inclusion of drainage systems and inclusion of climate change. This section provides a discussion regarding the UFR method which has been poorly discussed in previous literature, and the wider implications of the findings of this project on flood risk management.

On the method of the UFR approach there are key advantages that that methodology provides. Such as, the ability to identify hotspots, as the method pinpoint's locations in a catchment that have significant impact on flooding. This has implications for targeted mitigation efforts, as by identifying the areas that contribute the most to flooding, flood risk management efforts can be targeted more effectively. Resources can be allocated to prioritise these high-contributing areas for flood mitigation measures such as improved drainage systems flood-proofing measures for structures, and enhanced stormwater management. Additionally, conducting an analysis of the outputs generated from the UFR approach helps understand spatial patterns of flood contributions within the study areas. Through this I identified clusters or concentrations of high-contributing areas which indicate local factors or specific geographic features that amplify flood risk. For example, in Holbeck and Lin Dyke, the clustering was of high contributing catchments was mostly to the north of the catchment this also coincided with highly urbanised areas. In the case of Holbeck, majority of the defences are currently located in subunits J and K downstream of the balancing pond. Upon presenting these results to local authorities such as the LCC, the discussion concluded that sub-unit analysis highlighted subcatchments that would otherwise would not be considered as source areas such as subunit C. Hence it was concluded that, the tool as the potential to help this information helps target interventions in specific areas of a catchment, optimising the effectiveness of FRM strategies. The method used to implement the UFR approach is relatively straightforward making it accessible to a broader range of users.

There are significant limitations associated with the methodology, flooding is influenced by the hydrological connectivity of the landscape (Jencso et al., 2009; Trigg et al., 2013). Water from one area can flow into adjacent areas, leading to increased water levels and potential flooding. By turning off rainfall in one location, the approach does not account for the redistribution of water and potential downstream impacts. This results in an underestimation or overestimation of flood contributions in certain areas. Although, the work presented in this thesis, presented a new dataset and approach to incorporating drainage systems into flood models the UFR approach still does not capture the interactions accurately. For instance, natural or man-made drainage networks play a crucial role in flood dynamics. The method does not adequately consider the impact of turning off rainfall on the overall flow patterns within the drainage network. The diversion of water within the network can significantly influence flood patterns, and this interaction is not captured in the analysis of individual units.

The models used for this thesis were 2D only and deemed fit to achieve the aims and objectives. However, further work should consider the implications of using a 2D only or a 1D-2D linked model. The approach used will have implications for the FSAs identified using the UFR approach. For instance, in areas where topography, the river system or the drainage system is complex, a 1D-2D model would be more appropriate to capture the hydraulic complexities. Using 1D-2D coupled model will include additional detail and representation of the river and drainage network, which would improve the detail used in simulating flow behaviours in the river channel, drainage network and overland flow areas(Ochoa-Rodríguez, 2013; Pina et al., 2016; Teng et al., 2017). As with any modelling study however, there are significant considerations and trade-offs that should be appraised and have been previously identified and discussed within this chapter and in wider literature, such as computational demand, data availability and modelling skill.

The work in this thesis also highlights challenges associated with validating the results presented, a significant challenge being the lack of validation data available. Since surface water and pluvial flooding events often occur at small scales and in localised areas, this makes it difficult to collect comprehensive and high-quality validation data. Therefore, in agreement with studies that have highlighted this issue before this thesis, this also highlights the need for improved monitoring, and data collection that should be undertaken to address the challenge of validating modelling results from urban flood risk outputs (Molinari et al., 2019; Rubinato et al., 2019; Petersson et al., 2020). Additionally, a challenge within the topic of FSA which has not been mentioned or discussed before is the lack of validation of the source areas that have been identified. In all the studies that undertake the UFR methodology to identify FSAs little to no attention is given to confirming if the source areas identified do in fact, contribute the most to flood risk. It is likely, that traditional validation methods will not be suitable for the validation of FSAs hence may require the development of alternative validation methods, or use multiple sources such as surveys, field observations as well as traditional validation methods.

7.7 Summary of Further work

Within the context of the UFR approach further work can be undertaken to:

1. Include a socioeconomic vulnerability assessment such as population density, poverty levels, infrastructure quality and access to resources in the UFR approach framework. This will help identify areas with higher vulnerability to flood impacts such as low-income communities and areas with inadequate infrastructure. Overlying socioeconomic vulnerability data with the flood risk data, will help identify hotspots where the impact of flooding has severe consequences on the population.
2. Explore and evaluate various mitigation strategies that can be implemented in the identified high-risk areas. Incorporate the planned interventions, such as flood defences or stormwater management systems, into the models and assess their effectiveness in reducing flood risk.
3. Conduct a comprehensive cost-benefit analysis of the implemented mitigation strategies.
4. Address the lack of validation of source areas identified through the methodology.

Within the context of representing drainage systems:

1. Improve the robustness of the methodology by investigating different modelling assumptions such as using varying thresholds and assessing the sensitivity of the results to the changes in the inputs.
2. Explore the use of alternate methodologies and machine learning techniques that maybe applicable for the CAF dataset to improve on the current methodology of deriving drainage capacity.

7.8 Conclusions

In conclusion, I have made contributions to the field of urban flood risk management by addressing key research gaps in the topic of drainage representation in models, FSA identification, and the impact of climate change. The study identified the UFR approach as a key and innovative methodology for identifying FSAs within catchments and found the approach relied on modelling as essential tools. To advance this approach this thesis investigated the implications of software choice on identifying FSAs. The findings emphasised the importance of software choice in the UFR approach and its impact on flood source area rankings by comparing two modelling software, TUFLOW and HEC-RAS. The findings also demonstrated processes and models produced varying results, introducing uncertainty into decision-making processes, and hindering effective FRM. Moreover, the study recognised the lack of representation of socioeconomic factors within the current UFR approach framework which as the potential to perpetuate inequalities in resource allocation and other management strategies if the UFR approach is use drive decision making. To enhance the practical application of the UFR approach, the findings of this thesis emphasised the need to consider the requirements and perspectives of decision-makers, as well as incorporate socio-economic factors into the methodology. By understanding decision-makers needs and addressing socio-economic disparities, the UFR approach can be refined to improve flood risk management strategies and make the approach more holistic.

The analysis of the CAF dataset provided insight into the capacity and performance of the drainage system in the city of Leeds, as well as its response to climate change. The dataset provided a unique opportunity to improve representation of drainage systems in models, by providing a realistic representation of the current state of the drainage capacity within a catchment overall, addressing a significant research gap within this topic. However, the study also highlighted the need for site-specific analysis and consideration of catchment characteristics, as the impact of the CAF-derived drainage representation varied across different catchments. The research findings underscored the importance of accurate and realistic representation of drainage systems in flood models as even minor differences in drainage representation resulted in differences in the flood hazard experienced for certain catchments. The study also identified opportunities for further research such as exploring alternative methods for drainage capacity estimation using the CAF dataset, addressing missing data using geospatial techniques, and assessing the performance of different approaches to estimate capacity and to build on the limited body of research within this topic. Additionally, this thesis highlighted the importance of extending the application of the CAF dataset to other catchments in the UK, where the CAF data is available.

Lastly, the thesis investigated the impact of climate change on flood risk and FSA identification within Lin Dyke using the UFR approach. The analysis showed a significant influence of climate change factors on flood risk, as evidenced by the varying levels of flood risk and the changes in subunit contributions under different scenarios. Comparisons between the base scenario (BL) and scenarios that include climate change and drainage capacity (BLCC and BLCCDR) highlighted the increased hazard contribution of certain subunits. These findings emphasised the importance of incorporating climate change factors in FRM strategies and the UFR approach. Furthermore, the findings supported the stability and consistency of subunit rankings between scenarios through Kendall's tau-b values, indicating and reliable rankings under the different scenarios. The study identified opportunities for further research to focus on updating the current CAF data set to include the UKCP18 climate change allowances to be representative of the most up-to-date climate change projections, to improve the accuracy of the dataset and identification of FSAs. Overall, this thesis contributes to the field of modelling flood risk in urban areas and underscores the need for adaptive flood risk management strategies. The research findings provide a solid direction for further research that needs to be undertaken to advance the field of urban flood modelling and management.

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Appendix A

Evaluating the Unit Flood Response Approach using 2D rain-on-grid models.

A - 1: Catchment descriptors used to generate net rainfall inputs for the Holbeck Catchment (Bayliss, 1999; Institute of Hydrology, 1999)

Catchment Descriptor	Description
ALTBAR (m)	Mean catchment altitude
AREA(km^2)	Catchment drainage area
BFIHOST19	Base flow index is a measure of catchment responsiveness derived using the 29-class Hydrology Of Soil Types (HOST) classification.
CENTROID	Centroid of the catchment, in kilometres.
DDF	An estimate of the depth of precipitation for a specified duration and frequency.
DPLBAR (km)	Used to characterise catchment size and configuration.
DPSBAR (m/km)	Mean Drainage Path Slope provides an index of overall catchment steepness.
FARL	The Flood Attenuation by Reservoirs and Lakes (FARL) index, provides a guide to the degree of flood attenuation attributable to reservoirs and lakes in the catchment above a gauging station.
LDP (km)	Longest drainage path (in kilometres), defined by recording the greatest distance from a catchment node to the defined outlet.
PROPWET	This catchment wetness index represents the PROPortion of time soils are WET
SAAR (mm)	Average annual rainfall in the standard period (1961-1990) in millimetres.
SPRHOST (%)	Standard percentage runoff (%) associated with each HOST soil class.
URBEXT 2000	Index of urban and suburban land cover in 2000 expressed as a fraction.

A - 2: Comparison of the SWE and DWE implementation for 2D RoG modelling for a 5m DEM for the Holbeck Catchment

Hazard Category	Shallow Water	Diffusive wave
1	39201	38299

2	6668	1700
3	5343	698
4	863	488
5	616	566
6	29	34
Sum (H5:H6)	**645**	**600**

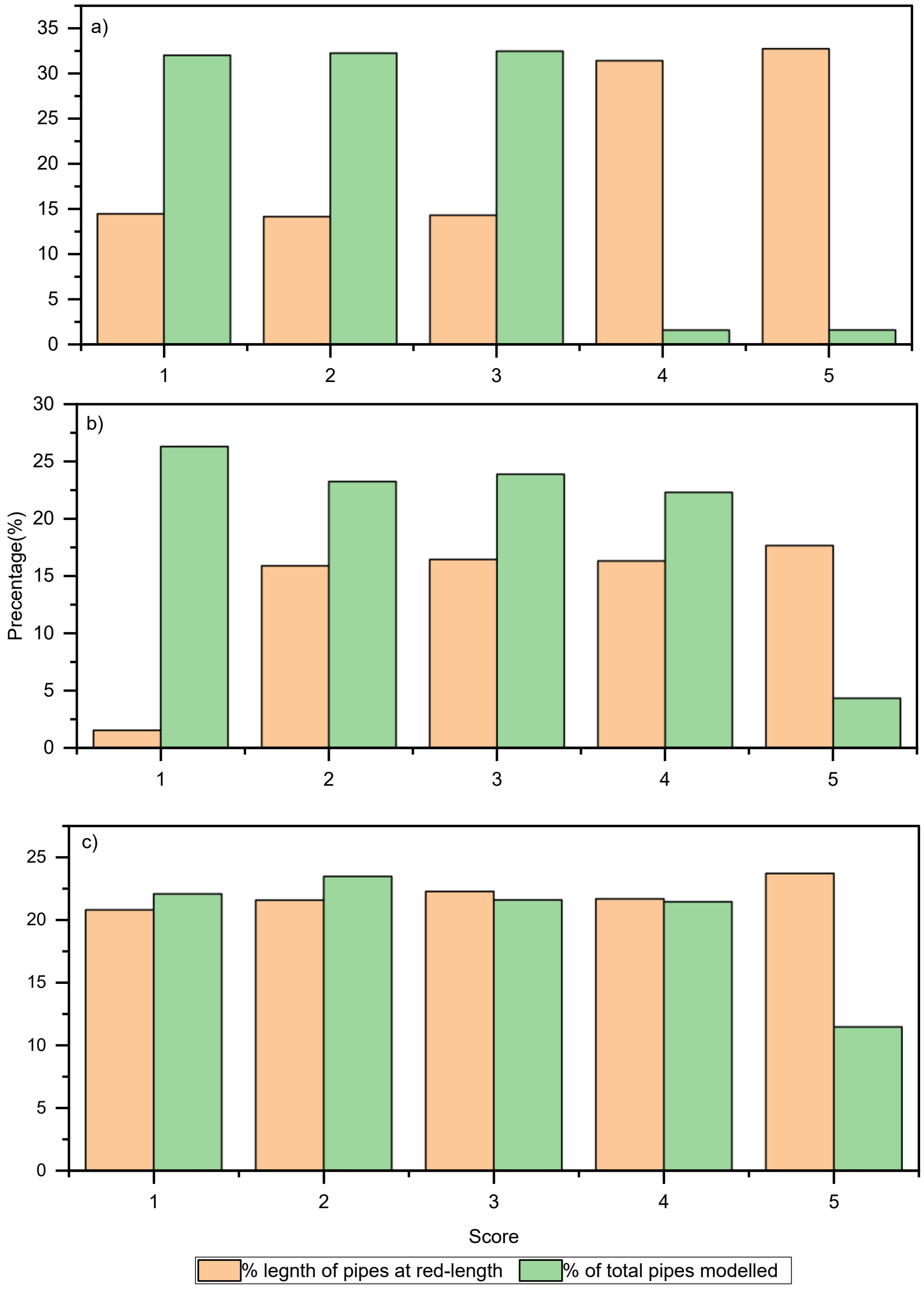
Appendix B

B - 1: Factors used to establish individual metrics of pipes and CSO performance

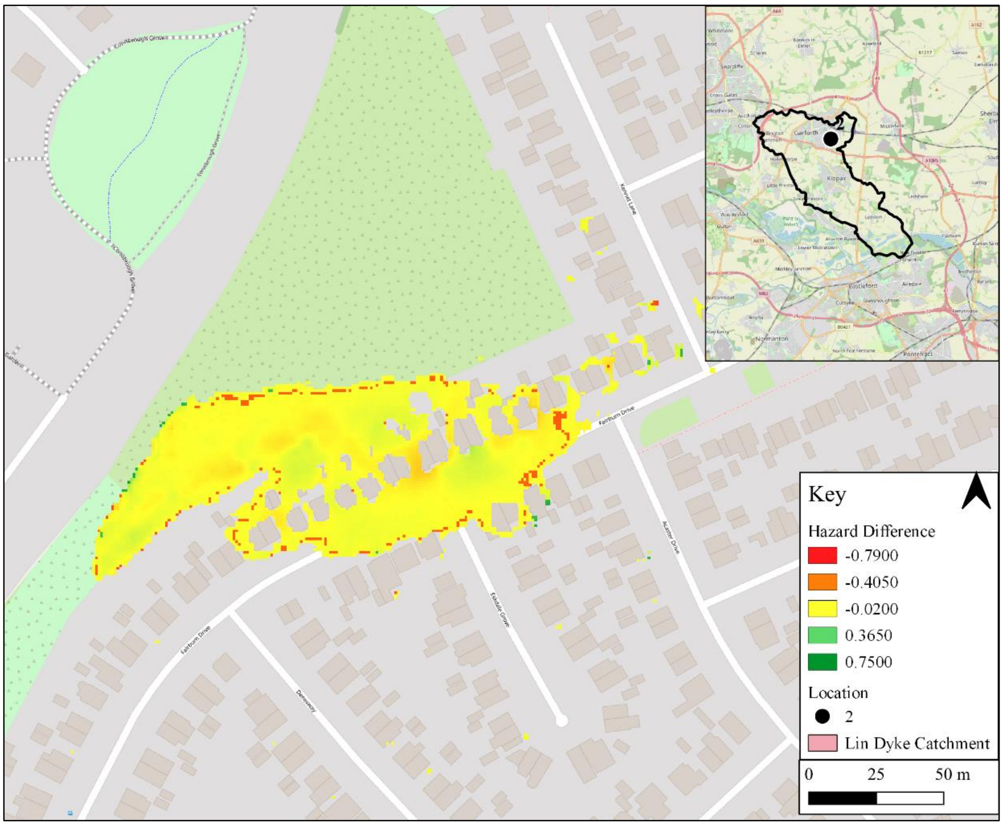
Pipes	**Combined Sewer Overflows**
Pipe full capacity/dry weather flow (DWF)[1]	Continuation pipe full capacity / DWF
Surcharge Return Periods	Potential of CSO spill[2]
Flooding Return Period	Number of CSO spills per year
Flood volume of the specified return period	Number of CSO spills per summer
	CSO spill volume per year

[1] Dry weather flow (DWF) is the domestic flows and trade flows to wastewater treatment works during a period without rain. DWF = Population*consumption rate + infiltration + trade flows

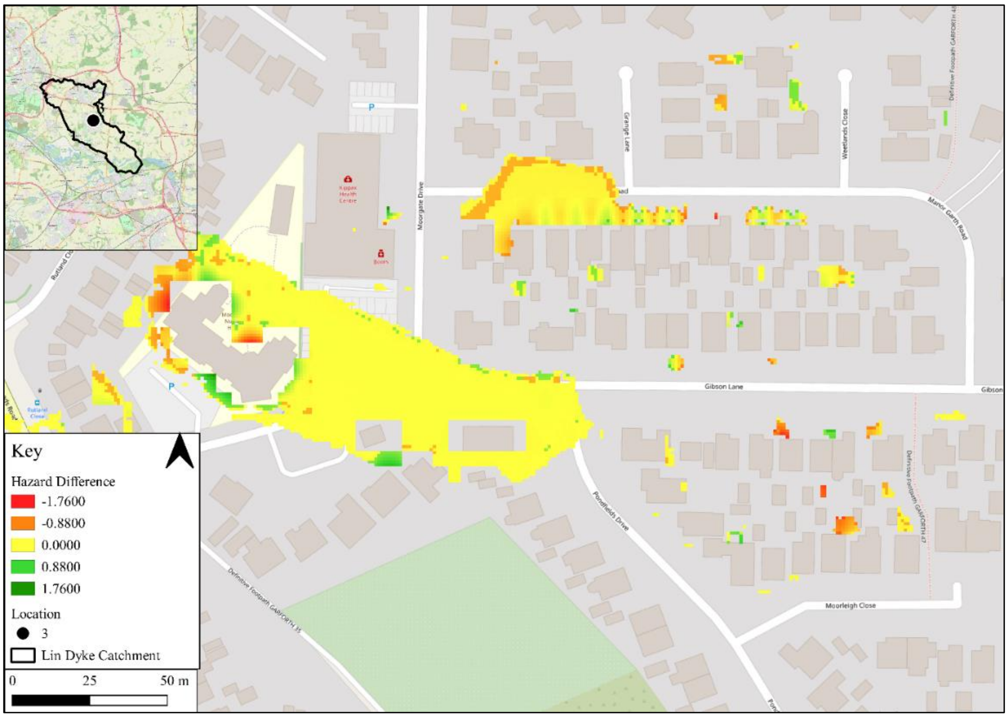
[2] Spill is defined as discharge in the first 12 hours and any discharge in the next 24-hour block is counted as 1 spill. If there is a 24-hour block with no discharge, the 12 hours and 24-hour block spill counting begins again.



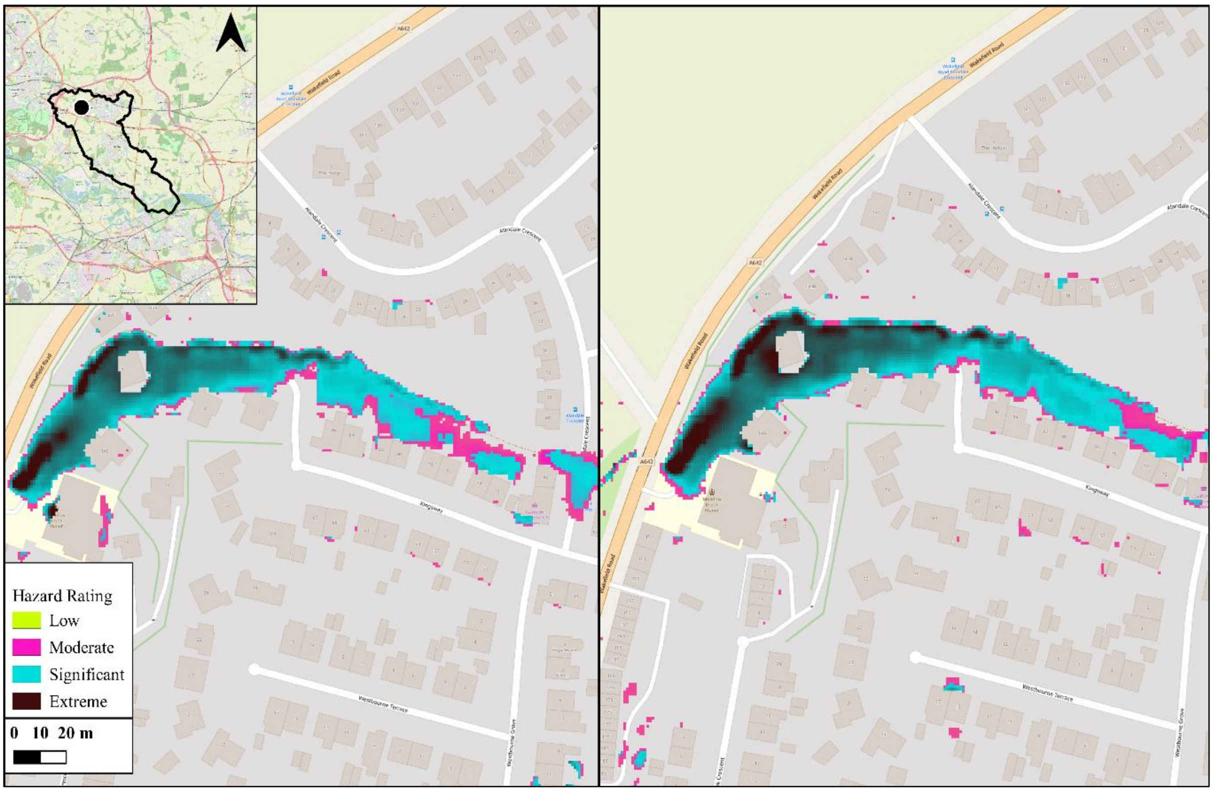
B - 2: Length of pipes as a percent at red length and total length of pipes modelled for catchment a) Holbeck, b) Wyke Beck, c) Lin Dyke for each risk score classification



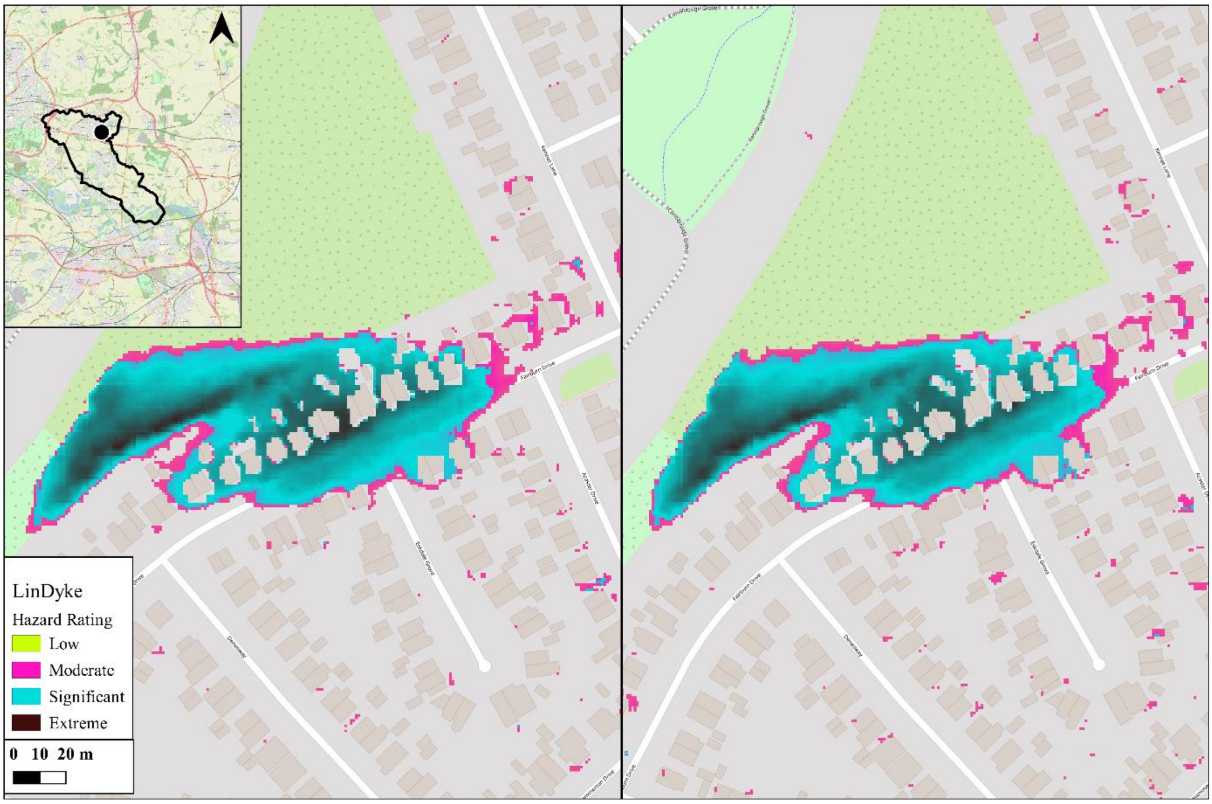
B - 3: Location 2 of 4 in Lin Dyke showing the difference in the extent of hazard rating between the NARR and CAFRR scenarios



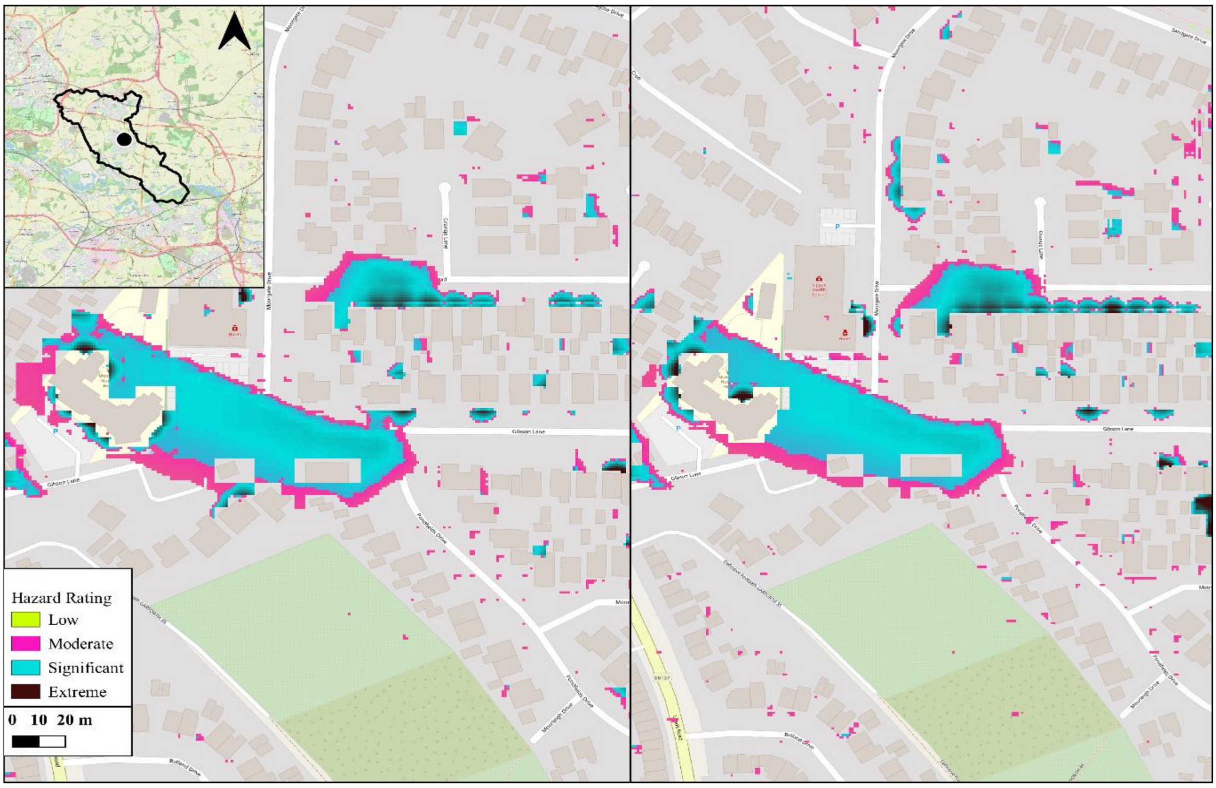
B - 4: Location 3 of 4 in Lin Dyke showing the difference in the extent of hazard rating between the NARR and CAFRR scenarios



B - 5: Location 1 of 4 in Lin Dyke showing the extent of hazard rating for the NARR (left) and CAFRR (right) scenarios.



B - 6: Location 2 of 4 in Lin Dyke showing the extent of hazard rating for the NARR (left) and CAFRR (right) scenarios.



B - 7: Location 3 of 4 in Lin Dyke showing the extent of hazard rating of the NARR (left) and CAFRR (right) scenarios

B - 8: Location 4 of 4 in Lin Dyke showing the extent of hazard rating of the NARR (left) and CAFRR (right) scenarios.

Appendix B